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(71) Applicant (for all designated States except US): **EASTMAN KODAK COMPANY** [US/US]; 343 State Street, Rochester, New York 14650 (US).

(72) Inventors; and

(75) Inventors/Applicants (for US only): **CAHALL, Scott,**

Christian [US/US]; 92 Manorshire Drive #6, Fairport, New York 14450 (US). **LEIDIG, Carl, Frederick** [US/US]; 99 Tamarack Drive, Rochester, New York 14622 (US).

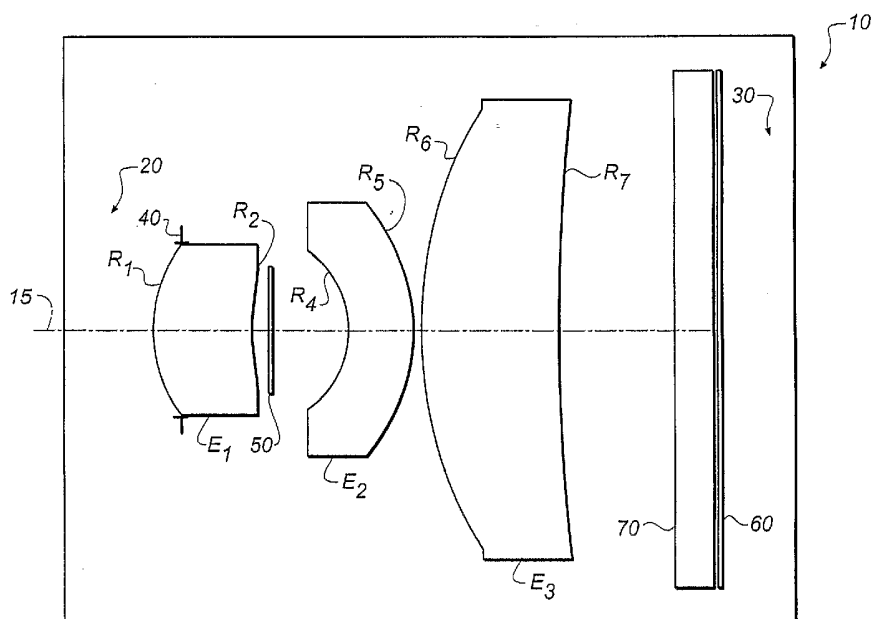
(74) Common Representative: **EASTMAN KODAK COMPANY**; 343 State Street, Rochester, NY 14650-2201 (US).

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[Continued on next page]

(54) Title: OBJECTIVE LENS SYSTEM HAVING THREE LENSES



(57) Abstract: An optical system is provided. In order from an object side to an image side, the optical system includes a first lens element having a positive power, a meniscus shape, and an object side surface. The object side surface of the first lens element is convex toward the object side. A second lens element has a negative power, a meniscus shape, and an object side surface. The object side surface of the second lens element is concave toward the object side. A third lens element has a positive power. An aperture stop is positioned on or in front of an object side of the first lens element.

Petitioner has added romanettes to pages (i)-(ii) and numbers to pages 31-53. Otherwise, it leaves the original page numbering.

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OBJECTIVE LENS SYSTEM HAVING THREE LENSES

FIELD OF THE INVENTION

The present invention relates generally to optical systems and,
5 more particularly, to optical systems having at least three lens elements useable
with, for example, light sensitive receivers and/or sensors.

BACKGROUND OF THE INVENTION

Optical systems useable with, for example, light sensitive receivers
and/or sensors are known. For example, US 6,560,037 discloses a single element
10 lens with an aperture stop adjacent to a distal surface of the lens element.
However, a single homogenous lens element such as that disclosed by US
6,560,037 does not affect the degree of optical imaging correction required to
produce the best resolution on sensors employing hundreds of thousands of pixels.

Optical systems having two lens groups or lens elements are also
15 known. For example, two lens group or element reverse telephoto designs are
disclosed in US 5,677,798; US 5,812,327; US 6,181,477; US 6,097,551; and US
patent application US 2002/0018303. A typical reverse-telephoto lens
configuration can be described as one where the first lens group or element is
negative in power and the second lens group or element is positive in power, when
20 proceeding sequentially from the most distal end of the lens to the sensor. This
arrangement causes the back focus of the lens system to be longer than the focal
length. The reverse-telephoto configuration is a design form that allows for a
generous space between the sensor and the lens element most proximal to the
sensor; this space is often used to position additional optics like infrared rejecting
25 filters or a sensor protective plate. Additionally, the reverse-telephoto lens
configuration may help reduce the magnitude of the oblique ray angles incident on
the sensor.

Other two lens element designs are disclosed that are not of the
aforementioned reverse-telephoto configuration. US 5,251,069; US 6,515,809;
30 US patent application 2003/0016452; US patent application 2003/0048549 are
such examples of non reverse-telephoto design forms comprised of two
groups/elements. Although these latter design forms may not possess the same

typical advantageous configuration of a reverse-telephoto lens, they emphasize other aspects of improvement like enhanced manufacturability, reduced cost or more compact size. In optical systems where there is little need for a space behind the lens for a thick plate or a stringent requirement on limiting the angle at which the chief ray is incident upon a sensor, the non reverse-telephoto design forms may be preferable. However, there is a limitation with any two group/element design form; image quality will generally be less than what it could be with three or more lens groups/elements. For compact lenses designed for miniature sensors with typically a million pixels or more, designs of three or more lens elements may be desirable to achieve a suitably high image resolution.

Optical systems having at least three lens elements are also known. US 6,441,971 B2; US 6,282,033; US 6,414,802; US 6,476,982; and JP2002162561 disclose three and four lens element/group systems designed for imaging with sensors, generally with an aperture stop at or near the most distal surface of the lens from the sensor.

Designs like those disclosed in US 6,282,033, US 6,414,802, US 6,476,982, and JP2002162561 are generally of the type comprised of four or more discrete lens elements that are assembled into at least three groups with an aperture of F/4 or less. Although excellent image quality may often be obtained with a sufficient number of optical surfaces, designs like these are expensive because of the number of lens elements that need to be manufactured and assembled versus designs with fewer elements. Furthermore, for a given application, it is difficult to achieve a short overall lens length when more lens elements are used. A useful figure-of-merit in comparing the shortness of lens designs is the ratio of the overall system length L , from the most distal vertex to the image plane, to the effective focal length of the lens f_0 . Applying this metric, US 6,282,033 discloses a lens with an overall system length of about 8 mm and a focal length of about 4.5 mm. The ratio of the overall system length to focal length for this lens is then a little less than 2. Furthermore, the preferred embodiment for US 6,282,033 is one comprising lenses all made from glass with spherical surfaces. The expense of making all elements from glass exceeds the cost of making elements from resin materials in high volume production. Designs

like those disclosed in US 6,476,982 and JP2002162561 consider hybrid glass-plastic forms with the use of aspheric surfaces for aberration correction on the plastic lens elements. JP2002162561 discloses lenses with focal lengths of approximately 5.6 mm and with overall system lengths a little greater than 10 mm; consequently, the ratio of overall system length to focal length is a little less than 2. US 6,476,982 discloses lenses with focal lengths of approximately 5.7 mm and with overall system lengths of approximately 7.35 mm, consequently, the ratio of overall system length to focal length is approximately 1.3. Designs like those disclosed US 6,414,802 B1 are comprised of all plastic elements. The overall system lengths of disclosed lenses are as low as 15 mm for a focal length of 10 mm; consequently, the ratio of overall system length to focal length is approximately 1.5. These lenses are deficient in the area of minimizing the ratio of overall system length to focal length partly because of the use of many lens elements and the inability to compress the design into short lengths.

Other lens designs, like those disclosed in US 6,441,971, are comprised of just three lens elements and have a relatively high light-collecting aperture of F/2.8 and wide field of view. The use of just three lens elements facilitates a more compact design than the lenses employing more elements. The designs disclosed in US 6,441,971 have a ratio of overall system length to focal length of approximately 1.25. Achieving this relatively short length is partly achieved by choice of lens materials. The disclosed designs utilize a positive power glass lens element in the most distal position from the sensor with index of refraction greater than those typical for most plastics and many glasses. For example, SK16 with $N_d=1.62041$ or C-ZLAF2 with $N_d=1.80279$ are used in the disclosed designs, whereas most common plastics like acrylic and polystyrene have $N_d < 1.6$. Additionally, the least expensive glass material type, BK7, has $N_d=1.517$. The refractive power of an air-material interface is greater when the index of refraction is higher and facilitates the design of a more compact system because lens thicknesses can generally be reduced; however, this design advantage comes at the expense of fabrication and material cost for the glass element(s). Designs that use the less expensive plastic resins with $N_d < 1.6$ (e.g.,

acrylic, polycarbonate) or that include one lens element using the least expensive type glass (e.g. BK7) will generally have a lower overall cost.

The designs disclosed in US 6,441,971 are disadvantaged in that they do not solve a problem that is important to the function of many sensors; namely, a significant reduction in the angles of rays incident upon the sensor. These designs have angles that exceed 20 degrees. It is important to reduce the angles of rays incident upon the sensor for several reasons. One is that it helps to improve the illumination uniformity on the sensor such that the corners are illuminated adequately relative to the center. Additionally, any dichroic-type filters (such as some infrared light rejection filters) will have properties that change versus angle of incidence; it is desirable to minimize these differences. Also, oblique rays incident on a sensor with light-collecting lenses (i.e., a microlenslet array) can become a problem if light associated with one lenslet over a pixel becomes imaged onto an adjacent pixel.

To overcome these issues, it is generally desirable to have all ray angles incident upon the sensor as small as possible. This requirement is often simplified to a constraint on the maximum chief ray angle. The chief ray angle is set by the lens exit pupil location. Lenses with exit pupil locations approaching infinity provide chief ray angles approaching zero, and are commonly referred to as telecentric. Practically, lenses with a high degree of telecentricity tend to come with increased complexity and increased overall length. As these are both key drivers in many imaging applications (e.g., camera-enabled phones and PDAs), some compromise must be made between them and the degree of telecentricity for a given lens solution (while preferably keeping the maximum chief ray angle less than about 20 degrees).

SUMMARY OF THE INVENTION

According to a first aspect of the invention, in order from an object side to an image side, an optical system includes a first lens element having a positive power, a meniscus shape, and an object side surface. The object side surface of the first lens element is convex toward the object side. A second lens element has a negative power, a meniscus shape, and an object side surface. The

object side surface of the second lens element is concave toward the object side. A third lens element has a positive power. An aperture stop is positioned on or in front of an object side of the first lens element.

5 **BRIEF DESCRIPTION OF THE DRAWINGS**

In the detailed description of the preferred embodiments of the invention presented below, reference is made to the accompanying drawings, in which:

FIG. 1 is a schematic cross sectional view of a first example
10 embodiment of the optical system;

FIG. 2 is a schematic cross sectional view of a second example
embodiment of the optical system;

FIG. 3 is a schematic cross sectional view of a third example
embodiment of the optical system;

15 FIG. 4 is a schematic cross sectional view of a fourth example
embodiment of the optical system;

FIG. 5 is a schematic cross sectional view of a fifth example
embodiment of the optical system;

20 FIG. 6 is a schematic cross sectional view of a sixth example
embodiment of the optical system; /

FIG. 7 is a schematic cross sectional view of a seventh example
embodiment of the optical system;

FIG. 8 is a schematic cross sectional view of an eighth example
embodiment of the optical system;

25 FIG. 9 is a schematic cross sectional view of a ninth example
embodiment of the optical system;

FIG. 10 is a schematic cross sectional view of a tenth example
embodiment of the optical system;

30 FIG. 11 is a through-focus MTF plot for the embodiment shown in
FIG. 1;

FIG. 12 is a through-focus MTF plot for the embodiment shown in
FIG. 2;

FIG. 13 is a through-focus MTF plot for the embodiment shown in FIG. 3;

FIG. 14 is a through-focus MTF plot for the embodiment shown in FIG. 4;

5 FIG. 15 is a through-focus MTF plot for the embodiment shown in FIG. 5;

FIG. 16 is a through-focus MTF plot for the embodiment shown in FIG. 6;

10 FIG. 17 is a through-focus MTF plot for the embodiment shown in FIG. 7;

FIG. 18 is a through-focus MTF plot for the embodiment shown in FIG. 8;

FIG. 19 is a through-focus MTF plot for the embodiment shown in FIG. 9; and

15 FIG. 20 is a through-focus MTF plot for the embodiment shown in FIG. 10.

DETAILED DESCRIPTION OF THE INVENTION

The present description will be directed in particular to elements forming part of, or cooperating more directly with, apparatus in accordance with the present invention. It is to be understood that elements not specifically shown or described may take various forms well known to those skilled in the art.

The example embodiments of the invention are illustrated in FIGS. 1-10, and Tables 1-10, respectively. In FIGS. 1-10 and Tables 1-10, an optical system 10 includes three lens elements E_1 , E_2 , and E_3 arranged in order, along an optical axis 15, from an object side 20 of the optical system 10 to an image side 30 of the optical system 10. An aperture stop 40 is located on an object side of lens element E_1 and at least one baffle 50 is located between lens elements E_1 and E_2 . A light sensitive receiver 60, for example, an image sensor or film, is located on an image side of lens element E_3 . An additional element 70, for example, a cover plate and/or filter, is located between light sensitive receiver 60 and lens element E_3 . Typical filters include infrared light rejection filters and/or light blurring filters (e.g. low-pass filters, band pass filters, etc.). The surface radii R of each

lens element E_1 , E_2 , and E_3 of optical system 10 are numbered beginning at the object side 20 and ending on the image side 30. In Tables 1-10, the thicknesses T_n of the lens elements and the airspaces between the lens elements are both labeled as "thickness" and are listed on the same line as the surface preceding the thickness. For example, the first thickness in Table 1 corresponds to the thickness of lens element E_1 . Similarly, the second thickness in Table 1 corresponds to the airspace between lens element E_1 and baffle 50. All thicknesses provided in Tables 1-10 are in millimeters. All indices and V- numbers (also known as Abbe numbers) are for the helium d line of the spectrum at a wavelength of 587.6 nm.

Referring to FIGS. 1 and 2 and Tables 1 and 2, respectively, first and second example embodiments are shown. Optical system 10 includes from object side 20 to image side 30 lens elements E_1 , E_2 , and E_3 . Lens element E_1 is a spherical singlet lens element having a positive power and a meniscus shape convex toward the object side 20. Lens element E_2 is a bi-aspheric singlet lens element having a negative power and a meniscus shape concave toward the object side 20. Lens element E_3 is a spherical singlet lens element having a positive power.

Aperture stop 40 is located on the object side surface of lens element E_1 . Alternatively, aperture stop 40 can be located spaced apart from the object side surface of lens element E_1 . Baffle 50, for example, a light vignetting aperture, is located between lens elements E_1 and E_2 . Alternatively, baffle 50 can be positioned on a surface of either or both of lens element E_1 and E_2 .

Lens elements E_1 , E_2 , and E_3 are made from glass, resin material (e.g. plastic), and resin material, respectively. However other material combination are possible. For example, lens elements E_1 , E_2 , and E_3 can be made from glass, resin material, and glass, respectively. Alternatively, lens elements E_1 , E_2 , and E_3 can be made from resin material, resin material, and glass, respectively. Each lens element E_1 , E_2 , and E_3 can be made from resin materials. When a resin material is used, the resin material can be of the type having a glass transition temperature, $T_g > 300$ °F. Nanocomposite optical material can also be used in any one or all of lens elements E_1 , E_2 , and E_3 .

The optical system 10 described in FIGS. 1 and 2 and Tables 1 and 2, respectively, has a half field of view in object space of at least 25 degrees; a relative aperture of less than $f/4$; and a maximum index of refraction that is less than 1.60. Additionally, the optical system 10 satisfies the condition $L/f_0 < 1.25$,
5 where L is the overall system length from the most distal vertex to the image plane and f_0 is the effective focal length of the lens.

Lens element E_1 , E_2 , and/or E_3 can be made from very low dispersion material (for example, Abbe V-number, $V_d > 65$). For example, in the example embodiment shown in FIG. 2 and TABLE 2, lens element E_1 is spherical
10 and made from very low dispersion material (Abbe V-number, $V_d > 65$, and more preferably Abbe V-number $V_d > 80$). Although similar to the embodiment shown in Fig. 1 and Table 1, the use of a very low dispersion material for lens element E_1 improves the polychromatic performance of optical system 10.

Referring to FIG. 3 and Table 3, a third example embodiment is
15 shown. Optical system 10 includes from object side 20 to image side 30 lens elements E_1 , E_2 , and E_3 . Lens element E_1 is a bi-aspheric singlet lens element having a positive power and a meniscus shape convex toward the object side 20. Lens element E_2 is a spherical singlet lens element having a negative power and a meniscus shape concave toward the object side 20. Lens element E_3 is a bi-
20 aspheric singlet lens element having a positive power.

Aperture stop 40 is located on the object side surface of lens element E_1 . Alternatively, aperture stop 40 can be located spaced apart from the object side surface of lens element E_1 . Baffle 50, for example, a light vignetting aperture, is located between lens elements E_1 and E_2 . Alternatively, baffle 50 can
25 be positioned on a surface of either or both of lens element E_1 and E_2 .

Lens elements E_1 , E_2 , and E_3 are made from resin material (e.g. plastic), resin material, and resin material, respectively. However other material combinations are possible. For example, lens elements E_1 , E_2 , and E_3 can made from resin material, glass, and resin material, respectively. When a resin material
30 is used, the resin material can be of the type having a glass transition temperature, $T_g > 300$ °F. Nanocomposite optical material can also be used in any one or all of

lens elements E_1 , E_2 , and E_3 . Alternatively, lens element E_1 , E_2 , and/or E_3 can be made from very low dispersion material (for example, Abbe V-number, $V_d > 65$).

The optical system 10 described in FIG. 3 Table 3, respectively, has a half field of view in object space of at least 25 degrees; a relative aperture of less than $f/4$; and a maximum index of refraction that is less than 1.60. Additionally, the optical system 10 satisfies the condition $L/f_0 < 1.25$, where L is the overall system length from the most distal vertex to the image plane and f_0 is the effective focal length of the lens.

Referring to FIGS. 4 and 5 and Tables 4 and 5, respectively, fourth and fifth example embodiments are shown. Optical system 10 includes from object side 20 to image side 30 lens elements E_1 , E_2 , and E_3 . Lens element E_1 is a bi-aspheric singlet lens element having a positive power and a meniscus shape convex toward the object side 20. Lens element E_2 is a bi-aspheric singlet lens element having a negative power and a meniscus shape concave toward the object side 20. Lens element E_3 is a spherical singlet lens element having a positive power.

Aperture stop 40 is located on the object side surface of lens element E_1 . Alternatively, aperture stop 40 can be located spaced apart from the object side surface of lens element E_1 . Baffle 50, for example, a light vignetting aperture, is located between lens elements E_1 and E_2 . Alternatively, baffle 50 can be positioned on a surface of either or both of lens element E_1 and E_2 .

Lens elements E_1 , E_2 , and E_3 are made from resin material (e.g. plastic), resin material, and resin material, respectively. However other material combination are possible. For example, lens elements E_1 , E_2 , and E_3 can be made from resin material, resin material, and glass, respectively. Nanocomposite optical material can also be used in any one or all of lens elements E_1 , E_2 , and E_3 . Alternatively, lens element E_1 , E_2 , and/or E_3 can be made from very low dispersion material (for example, Abbe V-number, $V_d > 65$).

The optical system 10 described in FIGS. 4 and 5 and Tables 4 and 5, respectively, has a half field of view in object space of at least 25 degrees; a relative aperture of less than $f/4$; and a maximum index of refraction that is less than 1.60. Additionally, the optical system 10 satisfies the condition $L/f_0 < 1.25$,

where L is the overall system length from the most distal vertex to the image plane and f_0 is the effective focal length of the lens.

When a resin material is used, the resin material can be of the type having a glass transition temperature, $T_g > 300$ °F. For example, in the example
5 embodiment shown in FIG. 5 and TABLE 5, all three lens elements E_1 , E_2 , and E_3 are made from resin materials of the type having a glass transition temperature, $T_g > 300$ °F, to allow for high temperature assembly operations, storage, or usage.

Referring to FIGS. 6, 7, and 8 and Tables 6, 7, and 8, respectively, sixth, seventh, and eighth example embodiments are shown. Optical system 10
10 includes from object side 20 to image side 30 lens elements E_1 , E_2 , and E_3 . Lens element E_1 is an aspheric singlet lens element having a positive power and a meniscus shape convex toward the object side 20. Either or both surfaces of lens element E_1 can be aspheric. Lens element E_2 is an aspheric singlet lens element having a negative power and a meniscus shape concave toward the object side 20.
15 Either or both surfaces of lens element E_2 can be aspheric. Lens element E_3 is an aspheric singlet lens element having a positive power. Either or both surfaces of lens element E_3 can be aspheric.

Aperture stop 40 is located on the object side surface of lens element E_1 . Alternatively, aperture stop 40 can be located spaced apart from the
20 object side surface of lens element E_1 . Baffle 50, for example, a light vignetting aperture, is located between lens elements E_1 and E_2 . Alternatively, baffle 50 can be positioned on a surface of either or both of lens element E_1 and E_2 .

Lens elements E_1 , E_2 , and E_3 are each made from resin materials (e.g. plastic). When a resin material is used, the resin material can be of the type
25 having a glass transition temperature, $T_g > 300$ °F. Nanocomposite optical material can also be used in any one or all of lens elements E_1 , E_2 , and E_3 . Alternatively, lens element E_1 , E_2 , and/or E_3 can be made from very low dispersion material (for example, Abbe V-number, $V_d > 65$).

The optical system 10 described in FIGS. 6, 7, and 8 and Tables 6,
30 7, and 8, respectively, has a half field of view in object space of at least 25 degrees; a relative aperture of less than $f/4$; and a maximum index of refraction that is less than 1.60. Additionally, the optical system 10 satisfies the condition

$L/f_0 < 1.25$, where L is the overall system length from the most distal vertex to the image plane and f_0 is the effective focal length of the lens.

Referring back to FIGS. 1-8 and Tables 1-8, respectively, each example embodiment of optical system 10 has an overall system length L from the object side surface of lens element E_1 to light sensitive receiver 60 is about 6 mm and the effective focal length f_0 for each of these example cases is about 5 mm, giving an L/f_0 ratio less than 1.20. Each example embodiment covers a semi-field of view of at least 28 degrees, is $F/2.8$ or faster, has a relative illumination in the corner which is approximately 50% of the illumination at the center of the image (or more), has a maximum distortion magnitude less than 4%, and constrains the maximum chief ray angle at the light sensitive receiver 10 or sensor plane to less than about 20 degrees with respect to the sensor plane normal.

Referring to FIG. 9 and Table 9, a ninth example embodiment is shown. Optical system 10 includes from object side 20 to image side 30 lens elements E_1 , E_2 , and E_3 . Lens element E_1 is an aspheric singlet lens element having a positive power and a meniscus shape convex toward the object side 20. In this embodiment, the image side surface of lens element E_1 is aspheric; however either surface of lens element E_1 can be aspheric. Lens element E_2 is a bi-aspheric singlet lens element having a negative power and a meniscus shape concave toward the object side 20. Lens element E_3 is an aspheric singlet lens element having a positive power. In this embodiment, the image side surface of lens element E_3 is aspheric; however either surface of lens element E_3 can be aspheric.

Aperture stop 40 is located spaced apart from the object side surface of lens element E_1 . Alternatively, aperture stop 40 can be located on the object side surface of lens element E_1 . Baffle(s) 50, for example, a light vignetting aperture, is located between lens elements E_1 and E_2 . Alternatively, baffle 50 can be positioned on a surface of either or both of lens element E_1 and E_2 . Another baffle(s) 50, for example, a light vignetting aperture and/or a glare stop, is located on an image side surface of lens element E_2 . Alternatively, this baffle(s) 50 can be located between lens elements E_2 and E_3 or on a surface of lens element E_3 .

Lens elements E_1 , E_2 , and E_3 are each made from resin materials (e.g. plastic). When a resin material is used, the resin material can be of the type having a glass transition temperature, $T_g > 300$ °F. Nanocomposite optical material can also be used in any one or all of lens elements E_1 , E_2 , and E_3 .

- 5 Alternatively, lens element E_1 , E_2 , and/or E_3 can be made from very low dispersion material (for example, Abbe V-number, $V_d > 65$).

- The optical system 10 described in FIG. 9 and Table 9 has a half field of view in object space of at least 25 degrees; a relative aperture of less than $f/4$; and a maximum index of refraction that is less than 1.60. Additionally, the
- 10 optical system 10 satisfies the condition $L/f_0 < 1.25$, where L is the overall system length from the most distal vertex to the image plane and f_0 is the effective focal length of the lens. The optical system 10 has an overall system length L from the aperture stop 40 to light sensitive receiver 60 is about 6.3 mm and the effective focal length f_0 is about 5.3 mm, giving an L/f_0 ratio less than 1.20. This example
- 15 embodiment covers a semi-field of view of at least 29 degrees, is $F/2.8$ or faster, has a relative illumination in the corner which is approximately 50% of the illumination at the center of the image (or more), has a maximum distortion magnitude less than 4%, and constrains the maximum chief ray angle at the light sensitive receiver 10 or sensor plane to less than about 22 degrees with respect to
- 20 the sensor plane normal.

- Referring to FIG. 10 and Table 10, a tenth example embodiment is shown. Optical system 10 includes from object side 20 to image side 30 lens elements E_1 , E_2 , and E_3 . Lens element E_1 is an aspheric singlet lens element having a positive power and a meniscus shape convex toward the object side 20.
- 25 In this embodiment, the image side surface of lens element E_1 is aspheric; however either surface of lens element E_1 can be aspheric. Lens element E_2 is a bi-aspheric singlet lens element having a negative power and a meniscus shape concave toward the object side 20. Lens element E_3 is an aspheric singlet lens element having a positive power. In this embodiment, the image side surface of
- 30 lens element E_3 is aspheric; however either surface of lens element E_3 can be aspheric.

Aperture stop 40 is located spaced apart from the object side surface of lens element E_1 . Alternatively, aperture stop 40 can be located on the object side surface of lens element E_1 . Baffle(s) 50, for example, a light vignetting aperture, is located between lens elements E_1 and E_2 . Alternatively, baffle 50 can be positioned on a surface of either or both of lens element E_1 and E_2 . Another baffle(s) 50, for example, a light vignetting aperture and/or a glare stop, is located on an image side surface of lens element E_2 . Alternatively, this baffle(s) 50 can be located between lens elements E_2 and E_3 or on a surface of lens element E_3 .

10 Lens elements E_1 , E_2 , and E_3 are each made from resin materials (e.g. plastic). When a resin material is used, the resin material can be of the type having a glass transition temperature, $T_g > 300$ °F. Nanocomposite optical material can also be used in any one or all of lens elements E_1 , E_2 , and E_3 . Alternatively, lens element E_1 , E_2 , and/or E_3 can be made from very low
15 dispersion material (for example, Abbe V-number, $V_d > 65$).

 The optical system 10 described in FIG. 10 and Table 10 has a half field of view in object space of at least 25 degrees; a relative aperture of less than $f/4$; and a maximum index of refraction that is less than 1.60. Additionally, the optical system 10 satisfies the condition $L/f_0 < 1.25$, where L is the overall system
20 length from the most distal vertex to the image plane and f_0 is the effective focal length of the lens. The optical system 10 has an overall system length L from the aperture stop 40 to light sensitive receiver 60 is about 7.13 mm and the effective focal length f_0 is about 6.0 mm, giving an L/f_0 ratio less than 1.20. This example embodiment covers a semi-field of view of at least 30 degrees, is $F/2.8$ or faster,
25 has a relative illumination in the corner which is approximately 50% of the illumination at the center of the image (or more), has a maximum distortion magnitude less than 4%, and constrains the maximum chief ray angle at the light sensitive receiver 10 or sensor plane to less than about 22 degrees with respect to the sensor plane normal.

30 Referring back to FIGS. 1-10 and Tables 1-10, respectively, each spherical lens element described in the example embodiments is made from low index materials ($N_d < 1.6$). As such, each spherical element can be made from

either optical glass or resin material with only very minor curve changes to these elements while the other lens elements of optical system 10 remain fixed (if desired). This allows for an optical system 10 to be prototyped with, for example, two glass spherical lens elements and one plastic lens element. Then, in
5 production, the two glass spherical lens elements can be replaced with spherical plastic elements with no changes to the other optical element(s) and minor or no changes to the mounting hardware (barrel, spacers, etc.).

In this manner, a manufacturer can switch between embodiments of the optical system 10 making use of the unique benefits of either optical glass
10 elements or plastic resin elements, as desired, at any point in the product lifecycle, for minimal additional cost. Generally, for glass, the primary benefits would be 1) a more thermally stable design, 2) a less-costly prototype, and 3) a quicker-to-produce prototype. For plastic resin, the primary benefits would be 1) a less-costly high volume production design and 2) a lighter weight design.

15 Lens elements E_1 , E_2 , and/or E_3 having an aspheric surface(s) of optical system 10 are typically made from resin materials. Alternatively, these elements can be made from glass; however, cost issues may prohibit this. Lens elements E_1 , E_2 , and/or E_3 having a-spherical surface(s) of optical system 10 can be made from either low index glass or resin material as is desired.

20 Suitable light sensitive receivers 60 include, for example, charged coupled devices (CCDs) and complementary metal-oxide sensors (CMOS). Additionally, the optical system 10 described above is adapted to function with these types of light sensitive receivers (sensors) having active diagonal dimensions of less than about eight millimeters. Alternatively, the optical system
25 10 described above can be scaled either up or down so as to function with light sensitive receivers (sensors) having larger or smaller active diagonal dimensions.

The optical system 10 described above lends itself to a variety of film and/or electronic imaging applications. Optical system 10 is particularly suitable for use in consumer mobile imaging applications, for example, camera-
30 enabled cellular phones and personal digital assistants (PDAs).

The through-focus MTF plots shown in FIGS. 11-20 are polychromatic (486 nm at 0.35, 538 nm at 1.00, and 597 nm at 0.50) for the

embodiments depicted in FIGS. 1-10 and Tables 1-10, respectively. The MTF plots are shown for 33 line pairs/mm.

The invention has been described in detail with particular reference to certain preferred embodiments thereof, but it will be understood that variations and modifications can be effected within the scope of the invention.

5

PARTS LIST

10	Optical system
15	Optical Axis
20	Object Side
30	Image Side
40	Aperture Stop
50	Baffle(s)
60	Light Sensitive Receiver
70	Additional Element
$E_1, E_2, \text{ and } E_3$	Lens element
$R_1 \dots R_N$	Surface Radii

TABLE 1

	SURF.	CLEAR AP.	RADIUS	THICKNESS	N _d	V _d
	OBJ	INF	INF	INF		
5	1	0.899(1)	1.484628	1.0480	1.517	64.2
	2	0.701	3.87226	0.2052		
	3	0.670(2)	PLANO	0.8341		
	4	0.841	-1.050646(3)	0.6998	1.590	30.8
	5	1.334	-1.709228(3)	0.0808		
10	6	2.305	4.370839	1.4786	1.530	55.9
	7	2.403	22.94755	1.2229		
	8	2.645	PLANO	0.4060	1.517	64.2
	9	2.703	PLANO	0.0250		
	10	2.709	PLANO			

NOTES:

- 1) APERTURE STOP
 2) VIGNETTING APERTURE
 20 3) ASPHERIC SURFACE DESCRIBED BY SAG EQUATION:

$$X(Y) = \frac{CY^2}{1 + \sqrt{1 - (k+1)C^2Y^2}} + DY^4 + EY^6 + FY^8 + GY^{10} + HY^{12} + IY^{14} + JY^{16}$$

25	SURF. 4	C= -0.951795 k= 0.000000	D= 0.74240079E-02 E= 0.10314786E00 F= -0.28038367E00 G= -0.93836004E-01	H= 0.5618976E00 I= 0.16700731E00 J= -0.90214939E00
30	SURF. 5	C= -0.585059 k= 0.000000	D= 0.48190457E-01 E= -0.26627216E-01 F= 0.16146376E-01 G= 0.51990544E-02	H= -0.29898661E-02 I= -0.2458555E-02 J= 0.10958537E-02

35

TABLE 2

	SURF.	CLEAR AP.	RADIUS	THICKNESS	N _d	V _d
	OBJ	INF	INF	INF		
5	1	0.893(1)	1.476838	1.0756	1.497	81.6
	2	0.702	4.122071	0.1710		
	3	0.680(2)	PLANO	0.8626		
	4	0.842	-0.9384097(3)	0.6563	1.590	30.8
	5	1.294	-1.458057(3)	0.0989		
10	6	2.239	4.379582	1.3959	1.530	55.9
	7	2.340	22.64364	1.3088		
	8	2.620	PLANO	0.4060	1.517	64.2
	9	2.690	PLANO	0.0250		
	10	2.700	PLANO			

15

NOTES:

1) APERTURE STOP

2) VIGNETTING APERTURE

20 3) ASPHERIC SURFACE DESCRIBED BY SAG EQUATION:

$$X(Y) = \frac{CY^2}{1 + \sqrt{1 - (k+1)C^2Y^2}} + DY^4 + EY^6 + FY^8 + GY^{10} + HY^{12} + IY^{14} + JY^{16}$$

25	SURF. 4	C= -1.065633 k= 0.000000	D= 0.90752938E-01 E= -0.75719461E-01 F= 0.15407556E00 G= -0.89984897E-02	H= 0.10958098E00 I= -0.11614418E00 J= -0.88493986E-01
30	SURF. 5	C= -0.685844 k= 0.000000	D= 0.58081303E-01 E= -0.18125923E-01 F= 0.20405245E-01 G= 0.75292315E-02	H= -0.26990959E-02 I= -0.3983865E-02 J= 0.18216606E-02

35

TABLE 3

	SURF.	CLEAR AP.	RADIUS	THICKNESS	N _d	V _d
	OBJ	INF	INF	INF		
5	1	0.919(1)	1.376075(3)	1.2964	1.530	55.9
	2	0.702	2.472313(3)	0.2841		
	3	0.700(2)	PLANO	0.5129		
	4	0.874	-1.421446	0.7083	1.590	30.8
	5	1.394	-3.015075	0.0929		
10	6	2.190	3.894110(3)	1.8301	1.530	55.9
	7	2.560	-100.1805(3)	0.8372		
	8	2.689	PLANO	0.4060	1.517	64.2
	9	2.718	PLANO	0.0250		
15	10	2.721	PLANO			

NOTES:

- 1) APERTURE STOP
 2) VIGNETTING APERTURE
 20 3) ASPHERIC SURFACE DESCRIBED BY SAG EQUATION:

$$X(Y) = \frac{CY^2}{1 + \sqrt{1 - (k+1)C^2Y^2}} + DY^4 + EY^6 + FY^8 + GY^{10} + HY^{12} + IY^{14} + JY^{16}$$

25	SURF. 1	C= 0.7497196 k= 0.1708289	D= 0.00000000 E= 0.00000000 F= 0.00000000 G= 0.00000000	H= 0.00000000 I= 0.00000000 J= 0.00000000
30	SURF. 2	C= 0.4153024 k= 6.5910530	D= 0.97584476E-01 E= -0.41616868E00 F= 0.11126273E01 G= -0.87165891E00	H= 0.00000000 I= 0.00000000 J= 0.00000000
35	SURF. 6	C= 0.2567981 k= -8.2623730	D= 0.21889224E-02 E= -0.28440338E-03 F= 0.58408327E-04 G= -0.23654137E-04	H= 0.00000000 I= 0.00000000 J= 0.00000000
40	SURF. 7	C= -0.0099923 k= 0.0000000	D= 0.47131521E-02 E= -0.24283270E-02 F= 0.27429091E-03 G= -0.24515189E-04	H= 0.00000000 I= 0.00000000 J= 0.00000000

TABLE 4

	SURF.	CLEAR AP.	RADIUS	THICKNESS	N _d	V _d
	OBJ	INF	INF	INF		
5	1	0.891(1)	1.359797(3)	0.9992	1.530	55.9
	2	0.714	2.439054(3)	0.2824		
	3	0.710(2)	PLANO	0.7366		
	4	0.865	-1.103848(3)	0.7315	1.590	30.8
	5	1.316	-1.60816(3)	0.0791		
10	6	2.106	4.776113	1.4501	1.530	55.9
	7	2.263	20.49335	1.2851		
	8	2.606	PLANO	0.4060	1.517	64.2
	9	2.693	PLANO	0.0250		
15	10	2.703	PLANO			

NOTES:

- 1) APERTURE STOP
 2) VIGNETTING APERTURE
 20 3) ASPHERIC SURFACE DESCRIBED BY SAG EQUATION:

$$X(Y) = \frac{CY^2}{1 + \sqrt{1 - (k+1)C^2Y^2}} + DY^4 + EY^6 + FY^8 + GY^{10} + HY^{12} + IY^{14} + JY^{16}$$

25	SURF. 1	C= 0.735404 k= 0.201923	D= 0.00000000 E= 0.00000000 F= 0.00000000 G= 0.00000000	H= 0.00000000 I= 0.00000000 J= 0.00000000
30	SURF. 2	C= 0.409995 k= 6.603307	D= 0.00000000 E= 0.00000000 F= 0.00000000 G= 0.00000000	H= 0.00000000 I= 0.00000000 J= 0.00000000
35	SURF. 4	C= -0.905922 k= 0.1618255	D= 0.00000000 E= 0.00000000 F= 0.00000000 G= 0.00000000	H= 0.00000000 I= 0.00000000 J= 0.00000000
40	SURF. 5	C= -0.6218287 k= -0.3796216	D= 0.00000000 E= 0.00000000 F= 0.00000000 G= 0.00000000	H= 0.00000000 I= 0.00000000 J= 0.00000000

TABLE 5

	SURF.	CLEAR AP.	RADIUS	THICKNESS	N _d	V _d
	OBJ	INF	INF	INF		
5	1	0.885(1)	1.359797(3)	0.9992	1.530	56.0
	2	0.713	2.439054(3)	0.2824		
	3	0.710(2)	PLANO	0.7366		
	4	0.866	-1.103848(3)	0.7315	1.560	32.0
	5	1.314	-1.60816(3)	0.0791		
10	6	2.090	4.776113	1.4501	1.530	56.0
	7	2.248	20.49335	1.2150		
	8	2.574	PLANO	0.4060	1.517	64.2
	9	2.664	PLANO	0.0250		
15	10	2.673	PLANO			

NOTES:

1) APERTURE STOP

2) VIGNETTING APERTURE

20 3) ASPHERIC SURFACE DESCRIBED BY SAG EQUATION:

$$X(Y) = \frac{CY^2}{1 + \sqrt{1 - (k+1)C^2Y^2}} + DY^4 + EY^6 + FY^8 + GY^{10} + HY^{12} + IY^{14} + JY^{16}$$

25	SURF. 1	C= 0.735404 k= 0.201923	D= 0.00000000 E= 0.00000000 F= 0.00000000 G= 0.00000000	H= 0.00000000 I= 0.00000000 J= 0.00000000
30	SURF. 2	C= 0.409995 k= 6.603307	D= 0.00000000 E= 0.00000000 F= 0.00000000 G= 0.00000000	H= 0.00000000 I= 0.00000000 J= 0.00000000
35	SURF. 4	C= -0.905922 k= 0.1618255	D= 0.00000000 E= 0.00000000 F= 0.00000000 G= 0.00000000	H= 0.00000000 I= 0.00000000 J= 0.00000000
40	SURF. 5	C= -0.6218287 k= -0.3796216	D= 0.00000000 E= 0.00000000 F= 0.00000000 G= 0.00000000	H= 0.00000000 I= 0.00000000 J= 0.00000000

TABLE 6

	SURF.	CLEAR AP.	RADIUS	THICKNESS	N _d	V _d
	OBJ	INF	INF	INF		
5	1	0.912(1)	1.372571(3)	1.1998	1.530	55.9
	2	0.702	2.521081(3)	0.2651		
	3	0.700(2)	PLANO	0.6574		
	4	0.875	-1.180721	0.8072	1.590	30.8
	5	1.395	-1.900876(3)	0.0979		
10	6	2.222	4.776188(3)	1.5097	1.530	55.9
	7	2.530	-100.073(3)	0.9695		
	8	2.688	PLANO	0.4060	1.517	64.2
	9	2.721	PLANO	0.0250		
15	10	2.724	PLANO			

NOTES:

1) APERTURE STOP

2) VIGNETTING APERTURE

20 3) ASPHERIC SURFACE DESCRIBED BY SAG EQUATION:

$$X(Y) = \frac{CY^2}{1 + \sqrt{1 - (k+1)C^2Y^2}} + DY^4 + EY^6 + FY^8 + GY^{10} + HY^{12} + IY^{14} + JY^{16}$$

25	SURF. 1	C= 0.7285598 k= 0.1488323	D= 0.00000000 E= 0.00000000 F= 0.00000000 G= 0.00000000	H= 0.00000000 I= 0.00000000 J= 0.00000000
30	SURF. 2	C= 0.3966552 k= 5.7201660	D= 0.7911972E-01 E= -0.30868440E00 F= 0.89123850E00 G= -0.68632905E00	H= 0.00000000 I= 0.00000000 J= 0.00000000
35	SURF. 5	C= 0.5260732 k= 0.0000000	D= 0.94505070E-02 E= 0.85824134E-04 F= 0.68959484E-03 G= 0.54915085E-03	H= 0.00000000 I= 0.00000000 J= 0.00000000
40	SURF. 6	C= 0.2093720 k= -5.7449510	D= 0.10169544E-02 E= -0.29482389E-03 F= 0.70745860E-04 G= -0.23252482E-04	H= 0.00000000 I= 0.00000000 J= 0.00000000
45	SURF. 7	C= -0.0099927 k= 0.0000000	D= 0.4427226E-02 E= -0.21136467E-02 F= 0.21423077E-03 G= -0.24599791E-04	H= 0.00000000 I= 0.00000000 J= 0.00000000

50

TABLE 7

	SURF.	CLEAR AP.	RADIUS	THICKNESS	N _d	V _d
	OBJ	INF	INF	INF		
5	1	0.927(1)	1.662800	1.1590	1.530	55.9
	2	0.774	5.720000(3)	0.2000		
	3	0.752(2)	PLANO	0.7570		
	4	0.897	-1.078370(3)	0.6980	1.590	30.8
	5	1.366	-1.541550(3)	0.0850		
10	6	2.440(2)	8.132540	1.6720	1.530	55.9
	7	2.752	-13.63016(3)	1.2700		
	8	3.040	PLANO	0.4000	1.517	64.2
	9	3.103	PLANO	0.0250		
15	10		PLANO			

NOTES:

- 1) APERTURE STOP
 2) VIGNETTING APERTURE
 20 3) ASPHERIC SURFACE DESCRIBED BY SAG EQUATION:

$$X(Y) = \frac{CY^2}{1 + \sqrt{1 - (k+1)C^2Y^2}} + DY^4 + EY^6 + FY^8 + GY^{10} + HY^{12} + IY^{14} + JY^{16}$$

25	SURF. 2	C= 0.1748252 k= 19.206420	D= -.10243737E-01 E= -0.92708580E-02 F= -0.12141643E-01 G= -0.47005287E-02	H= 0.00000000 I= 0.00000000 J= 0.00000000
30	SURF. 4	C= -0.9273255 k= 0.0000000	D= 0.44252743E-01 E= 0.68139433E-01 F= 0.24501737E-01 G= -0.59331288E-01	H= 0.35363612E-03 I= 0.35807664E-01 J= 0.00000000
35	SURF. 5	C= -0.6486977 k= 0.0000000	D= 0.59612810E-01 E= 0.16783025E-01 F= 0.1574746E-01 G= -0.30817803E-02	H= -0.3108184E-02 I= 0.15326313E-02 J= 0.00000000
40	SURF. 7	C= 0.07336671 k= 0.0000000	D= -0.18042455E-01 E= 0.14764062E-02 F= -0.17633960E-03 G= 0.70521326E-05	H= 0.00000000 I= 0.00000000 J= 0.00000000

TABLE 8

	SURF.	CLEAR AP.	RADIUS	THICKNESS	N _d	V _d
	OBJ	INF	INF	INF		
5	1	0.927(1)	1.662800	1.1590	1.530	55.9
	2	0.774	5.720000(3)	0.2000		
	3	0.752(2)	PLANO	0.7570		
	4	0.873	-1.078370(3)	0.6980	1.590	30.8
	5	1.310(2)	-1.541550(3)	0.0850		
10	6	2.462	8.132540	1.6720	1.530	55.9
	7	2.751(2)	-13.63016(3)	1.2700		
	8	3.041	PLANO	0.4000	1.517	64.2
	9	3.103	PLANO	0.0250		
15	10		PLANO			

NOTES:

1) APERTURE STOP

2) VIGNETTING APERTURE

20 3) ASPHERIC SURFACE DESCRIBED BY SAG EQUATION:

$$X(Y) = \frac{CY^2}{1 + \sqrt{1 - (k+1)C^2Y^2}} + DY^4 + EY^6 + FY^8 + GY^{10} + HY^{12} + IY^{14} + JY^{16}$$

25	SURF. 2	C= 0.1748252 k= 19.206420	D= -.10243737E-01 E= -0.92708580E-02 F= -0.12141643E-01 G= -0.47005287E-02	H= 0.00000000 I= 0.00000000 J= 0.00000000
30	SURF. 4	C= -0.9273255 k= 0.0000000	D= 0.44252743E-01 E= 0.68139433E-01 F= 0.24501737E-01 G= -0.59331288E-01	H= 0.35363612E-03 I= 0.35807664E-01 J= 0.00000000
35	SURF. 5	C= -0.6486977 k= 0.0000000	D= 0.59612810E-01 E= 0.16783025E-01 F= 0.1574746E-01 G= -0.30817803E-02	H= -0.3108184E-02 I= 0.15326313E-02 J= 0.00000000
40	SURF. 7	C= 0.07336671 k= 0.0000000	D= -0.18042455E-01 E= 0.14764062E-02 F= -0.17633960E-03 G= 0.70521326E-05	H= 0.00000000 I= 0.00000000 J= 0.00000000

TABLE 9

	SURF.	CLEAR AP.	RADIUS	THICKNESS	N _d	V _d
	OBJ	INF	INF	INF		
5	STO	0.981(1)	INF	0.050		
	2	1.003	1.66280	1.159	1.530	55.9
	3	0.822	5.72000(4)	0.153		
	4	0.800(2)	INF	0.076		
	5	0.800(2)	INF	0.728		
10	6	0.907	-1.11970(4)	0.698	1.583	30.1
	7	1.362	-1.61415(4)	-0.316		
	8	1.431(3)	INF	0.401		
	9	2.155	8.13254	1.765	1.530	55.9
	10	2.578	9.83558(4)	1.273		
15	11	2.900	PLANO	0.300	1.523	58.6
	12	2.943	PLANO	0.025		
	IMA	2.949	PLANO			

NOTES:

- 20 1) APERTURE STOP
 2) VIGNETTING APERTURE
 3) GLARE STOP

4) ASPHERIC SURFACE DESCRIBED BY SAG EQUATION:

$$X(Y) = \frac{CY^2}{1 + \sqrt{1 - (k+1)C^2Y^2}} + DY^4 + EY^6 + FY^8 + GY^{10} + HY^{12} + IY^{14} + JY^{16}$$

25	SURF. 3	C= 0.1748252 k= 19.206420	D= -0.10243737E-01 E= -0.92708580E-02 F= -0.12141643E-01 G= -0.47005287E-02	H= 0.00000000 I= 0.00000000 J= 0.00000000
30	SURF. 6	C= -0.8930964 k= 0.0000000	D= 0.41014658E-01 E= 0.81738929E-01 F= -0.31897343E-00 G= 0.80497156E-00	H= -0.86008994E-00 I= 0.30775966E-00 J= 0.00000000
35	SURF. 7	C= -0.6195211 k= 0.0000000	D= 0.64314342E-01 E= -0.53249786E-02 F= 0.37429655E-01 G= -0.19403391E-01	H= 0.3905023E-02 I= 0.3341013E-04 J= 0.00000000
40	SURF. 10	C= 0.1016717 k= 0.0000000	D= -0.18420485E-01 E= 0.14508599E-02 F= -0.17794895E-03 G= 0.70228893E-05	H= 0.20077432E-07 I= 0.56230036E-08 J= 0.599365E-09
45				

TABLE 10

	SURF.	CLEAR AP.	RADIUS	THICKNESS	N _d	V _d
	OBJ	INF	INF	INF		
5	STO	1.110(1)	INF	0.050		
	2	1.137	1.88232	1.312	1.530	55.9
	3	0.931	6.47514(3)	0.173		
	4	0.905(2)	INF	0.076		
	5	0.905(2)	INF	0.834		
10	6	1.024	-1.26752(3)	0.790	1.583	30.1
	7	1.549	-1.82725(3)	-0.367		
	8	1.630(2)	INF	0.463		
	9	2.719	9.20618	2.022	1.530	55.9
	10	3.130	11.13405(3)	1.453		
15	11	3.417	PLANO	0.300	1.523	58.6
	12	3.447	PLANO	0.025		
	IMA	3.452	PLANO			

NOTES:

- 20 1) APERTURE STOP
 2) VIGNETTING APERTURE
 3) ASPHERIC SURFACE DESCRIBED BY SAG EQUATION:

$$X(Y) = \frac{CY^2}{1 + \sqrt{1 - (k+1)C^2Y^2}} + DY^4 + EY^6 + FY^8 + GY^{10} + HY^{12} + IY^{14} + JY^{16}$$

25	SURF. 3	C= 0.1544368 k= 19.206420	D= -0.70615316E-02 E= -0.49871689E-02 F= -0.50968902E-02 G= -0.15398137E-02	H= 0.00000000 I= 0.00000000 J= 0.00000000
30	SURF. 6	C= -0.7889422 k= 0.0000000	D= 0.28273501E-01 E= 0.43970671E-01 F= -0.13390053E-00 G= 0.26369506E-00	H= -0.21986646E-00 I= 0.61393227E-01 J= 0.00000000
35	SURF. 7	C= -0.5472705 k= 0.0000000	D= 0.44335164E-01 E= -0.2864521E-02 F= 0.1571244E-01 G= -0.63562225E-02	H= 0.9982486E-03 I= 0.66647972E-05 J= 0.00000000
40	SURF. 10	C= 0.0898146 k= 0.0000000	D= -0.12698182E-01 E= 0.78047612E-03 F= -0.74700454E-04 G= 0.23005797E-05	H= 0.51324328E-08 I= 0.11217011E-08 J= 0.93302613E-10

45

CLAIMS:

1. An optical system comprising in order from an object side to and image side:
 - a first lens element having a positive power, a meniscus shape, and an object side surface, the object side surface of the first lens element being convex toward the object side;
 - a second lens element having a negative power, a meniscus shape, and an object side surface, the object side surface of the second lens element being concave toward the object side;
 - a third lens element having a positive power; and
 - an aperture stop positioned on an object side of the first lens element.
2. The optical system according to Claim 1, wherein the first lens element is a singlet.
3. The optical system according to Claim 1, wherein the aperture stop is positioned on the object side surface of the first lens element
4. The optical system according to Claim 1, further comprising:
 - a light vignetting aperture located between the first and second lens elements.
5. The optical system according to Claim 1, wherein the first, second, and third lens elements are made from resin materials.
6. The optical system according to Claim 1, the optical system having an effective focal length f_0 , a total length L defining the distance between the vertex of the object side surface of the first lens element and an image plane located at an air equivalent back focus, wherein the optical system satisfies the condition $L/f_0 < 1.20$.

7. The optical system according Claim 6, wherein the first lens element is made from a material having an Abbe V-number, $V_d > 65$.

5 8. The optical system according Claim 1, wherein the optical system has a half field of view in object space of at least 25 degrees.

9. The optical system according Claim 1, wherein the optical system has a relative aperture of less than $f/4$.

10 10. The optical system according Claim 1, wherein all of the lens elements have an index of refraction of less than 1.60.

11. The optical system according to Claim 1, wherein the first lens element is made from a material having an Abbe V-number, $V_d > 65$.

15

12. The optical system according to Claim 1, wherein at least one of the lens elements is made from a resin material having a glass transition temperature, $T_g > 300^\circ\text{F}$.

20 13. The optical system according to Claim 1, wherein at least one of the lens elements is made from a nanocomposite optical material.

14. The optical system according to Claim 1, wherein the first lens element is spherical, the second lens element is aspheric, and the third lens
25 element is spherical.

15. The optical system according to Claim 1, wherein the first lens element is spherical, the second lens element is bi-aspheric, and the third lens element is spherical.

30

16. The optical system according to Claim 15, wherein the first lens element is made from a glass, the second lens element is made from a resin material, and the third lens element is made from a glass.

5 17. The optical system according to Claim 15, wherein the first lens element is made from a glass, the second lens element is made from a resin material, and the third lens element is made from a resin material.

10 18. The optical system according to Claim 15, wherein the first lens element is made from a resin material, the second lens element is made from a resin material, and the third lens element is made from a glass.

15 19. The optical system according to Claim 15, wherein the first, second, and third lens elements are made from resin materials.

20 20. The optical system according to Claim 1, wherein the first lens element is aspheric, the second lens element is spherical, and the third lens element is aspheric.

21. The optical system according to Claim 20, wherein the first lens element is made from a resin material, the second lens element is made from a glass, and the third lens element is made from a resin material.

22. The optical system according to Claim 20, wherein the first, second, and third lens elements are made from resin materials.

23. The optical system according to Claim 1, wherein the first lens element is aspheric, the second lens element is aspheric, and the third lens element is spherical.

24. The optical system according to Claim 23, wherein the first lens element is made from a resin material, the second lens element is made from a resin material, and the third lens element is made from a glass.

25. The optical system according to Claim 23, wherein the first, second, and third lens elements are made from resin materials.

26. The optical system according to Claim 1, wherein the first
5 lens element is aspheric, the second lens element is aspheric, and the third lens element is aspheric.

27. The optical system according to Claim 26, wherein the first, second, and third lens elements are made from resin materials.

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28. The optical system according to Claim 1, wherein the maximum chief ray angle in air with respect to the image surface normal is less than 20° , where chief rays are defined as rays that pass through the center of the aperture stop.

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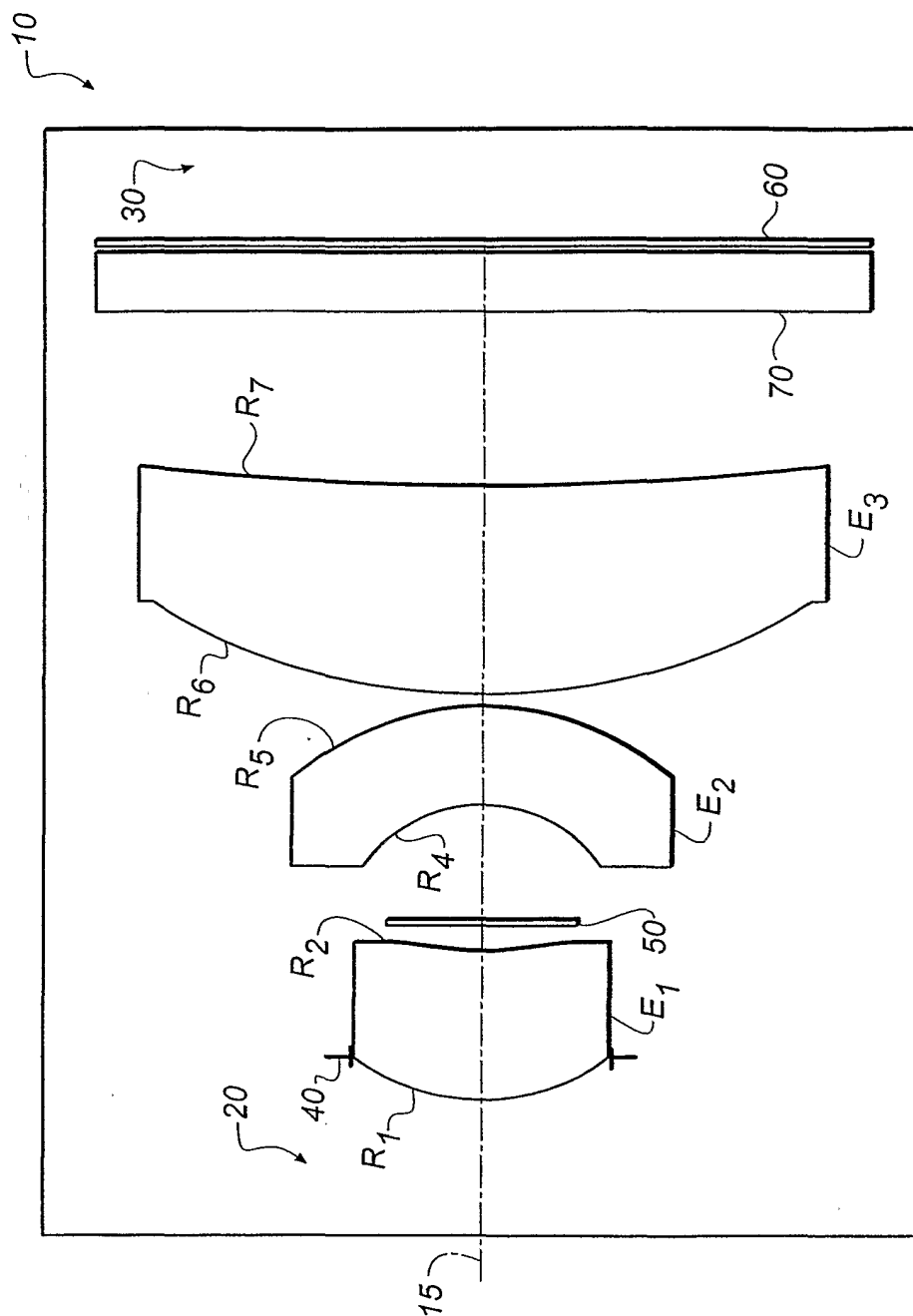


FIG. 1

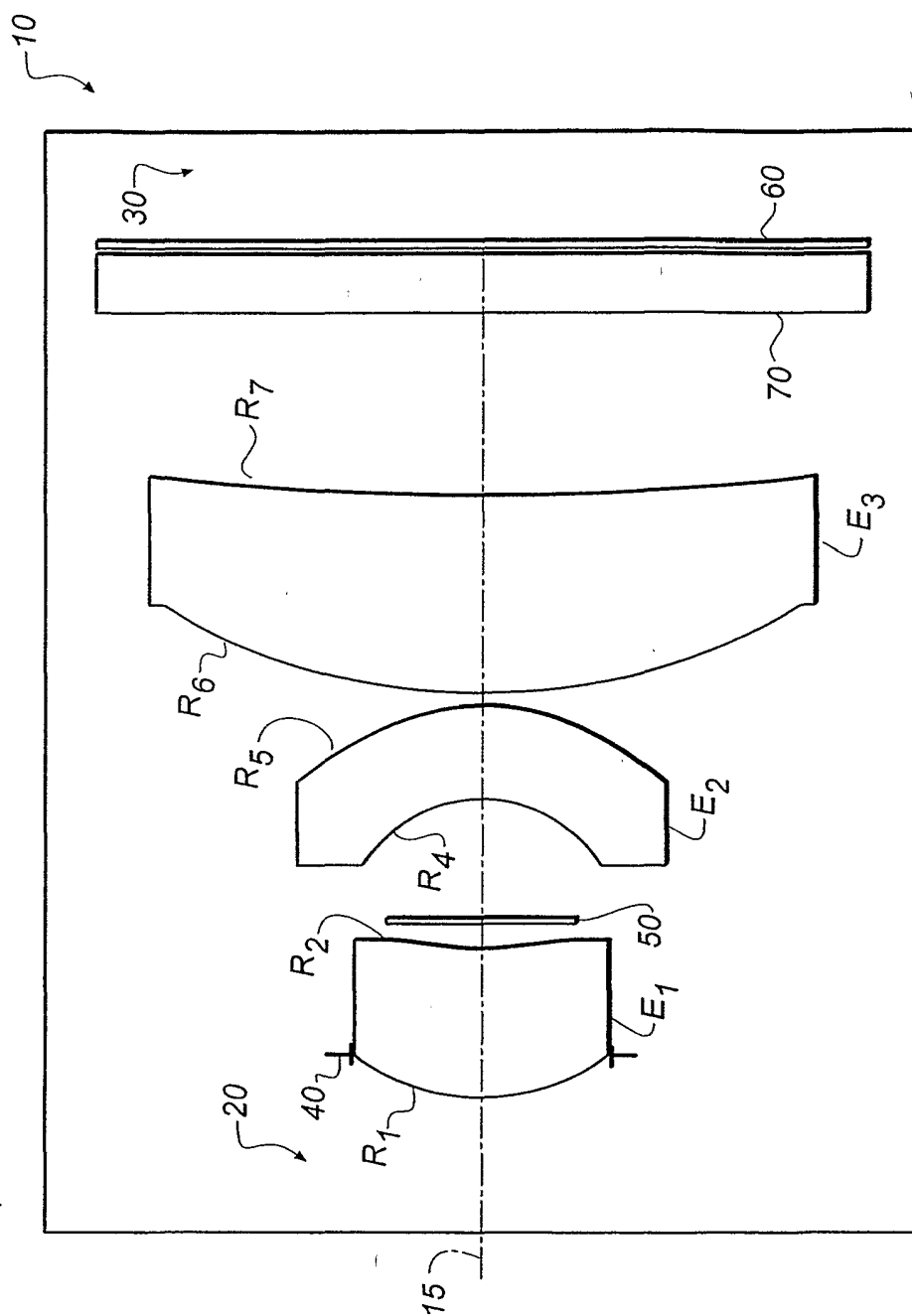


FIG. 2

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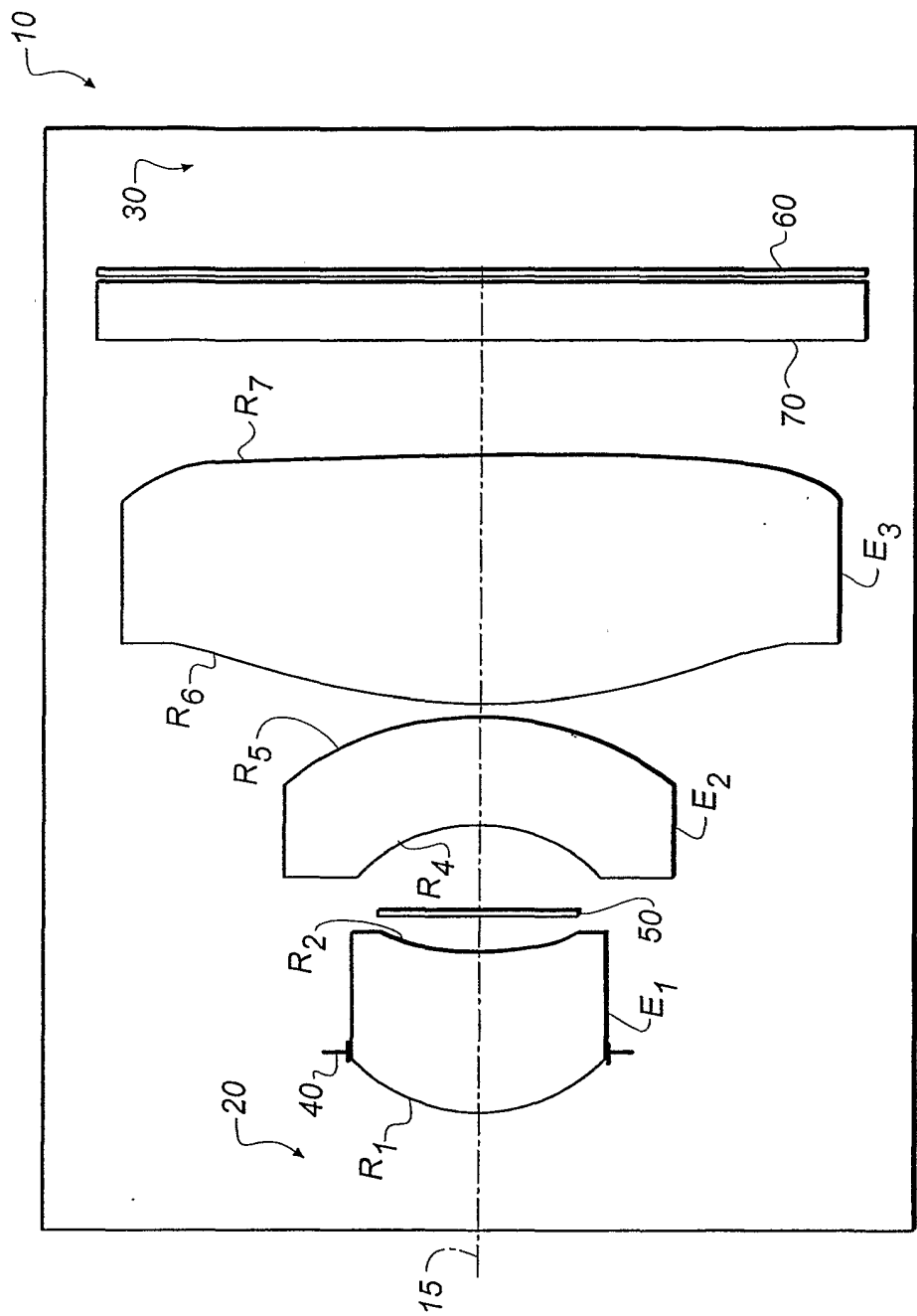


FIG. 3

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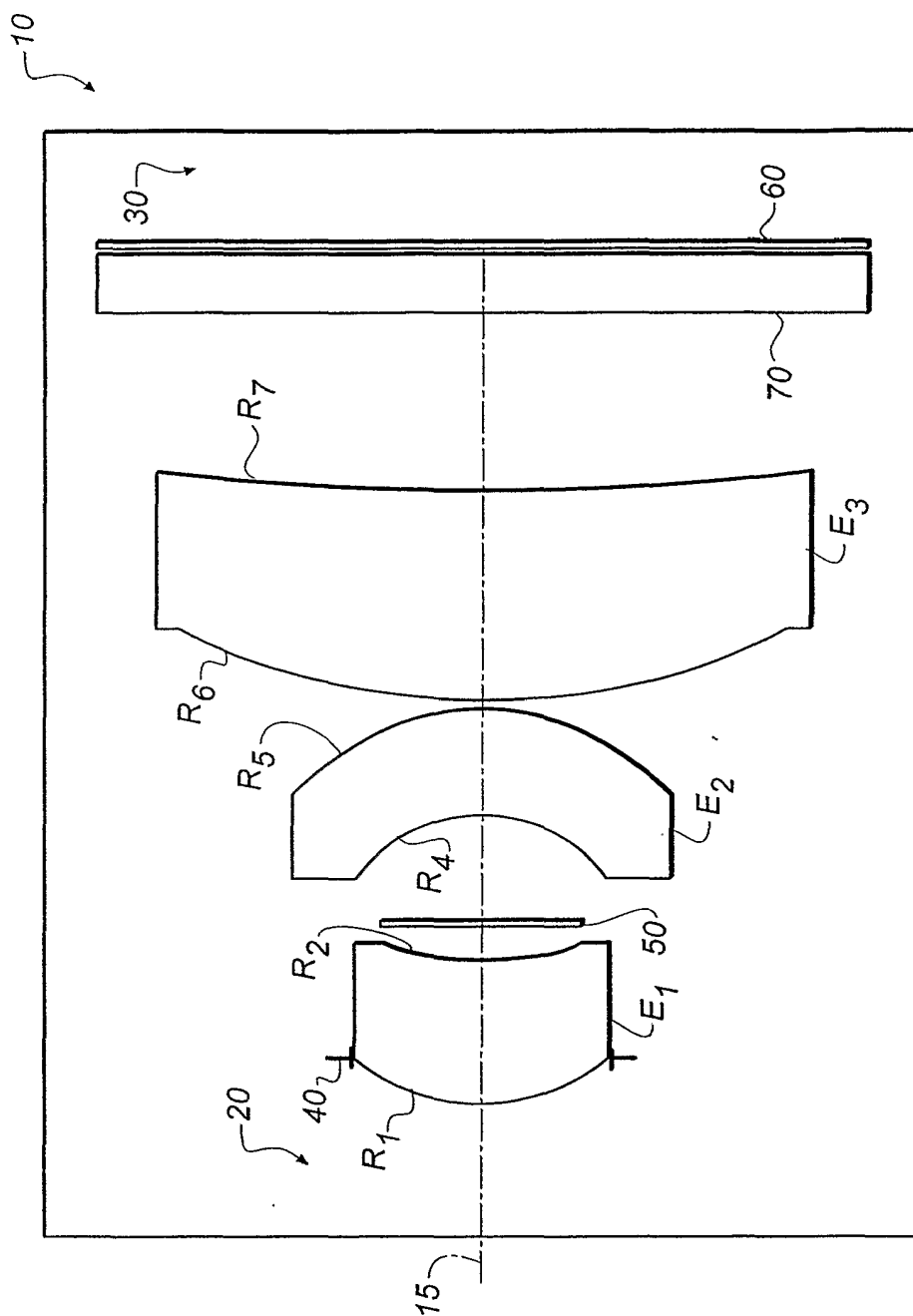


FIG. 4

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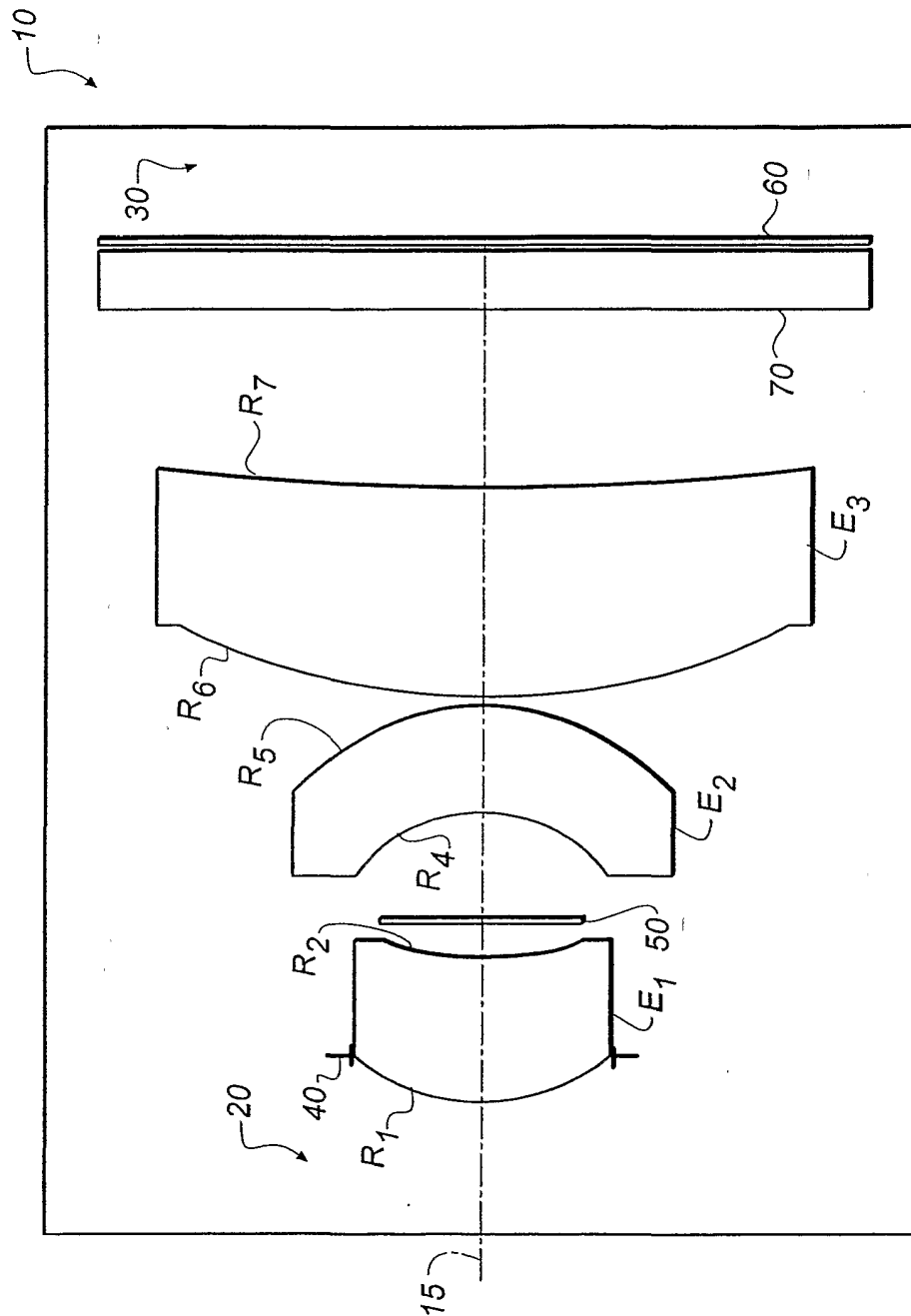


FIG. 5

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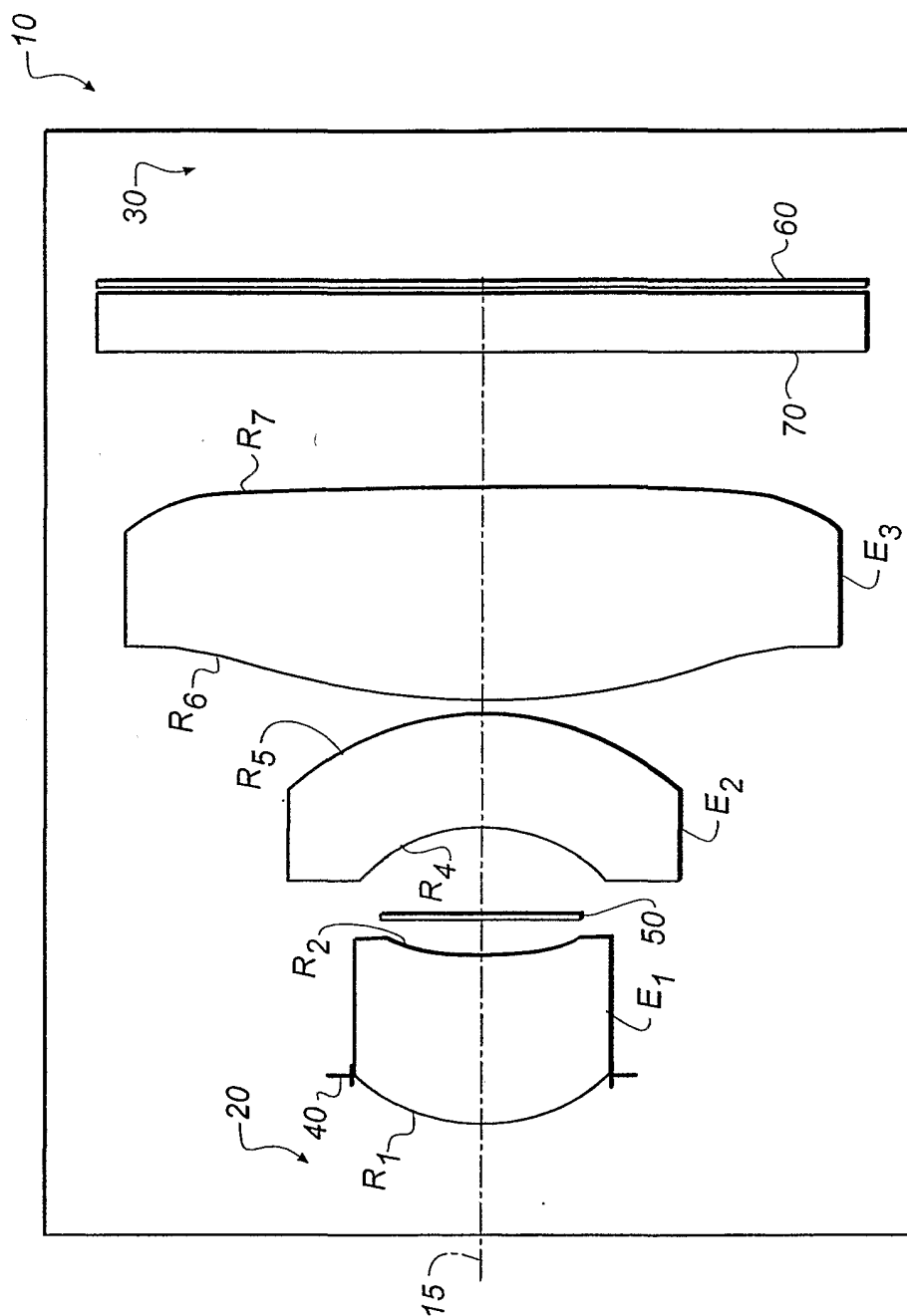


FIG. 6

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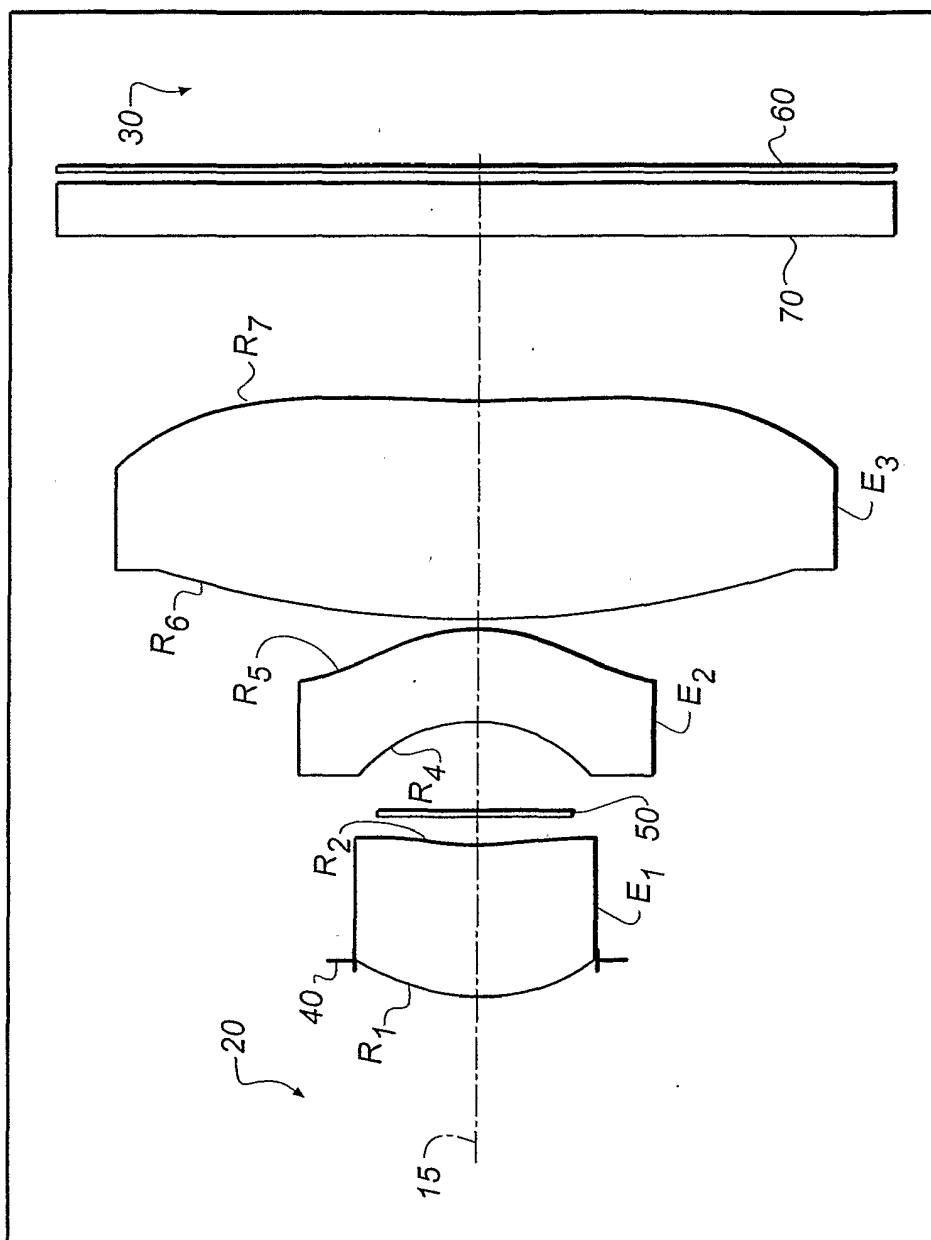


FIG. 7

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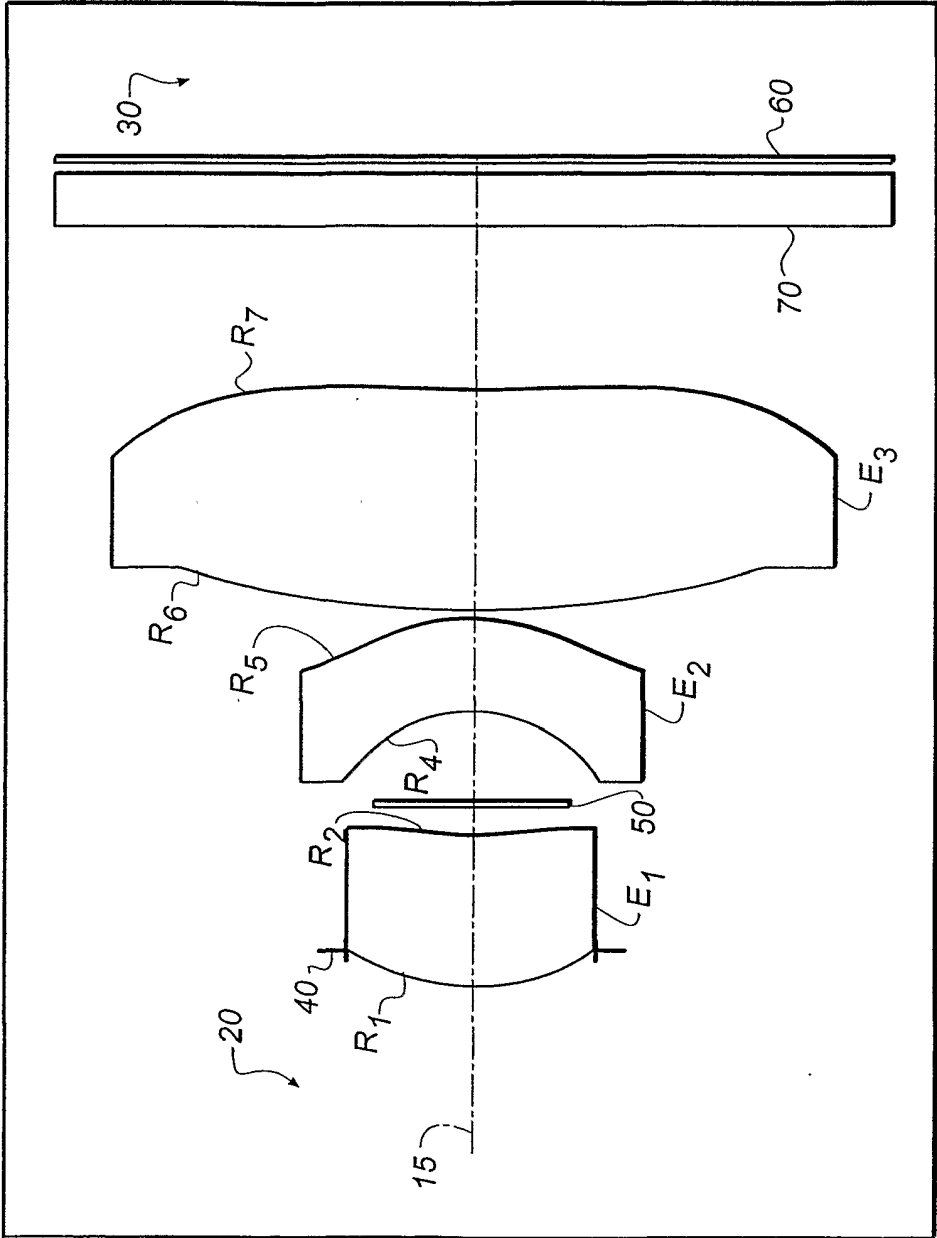


FIG. 8

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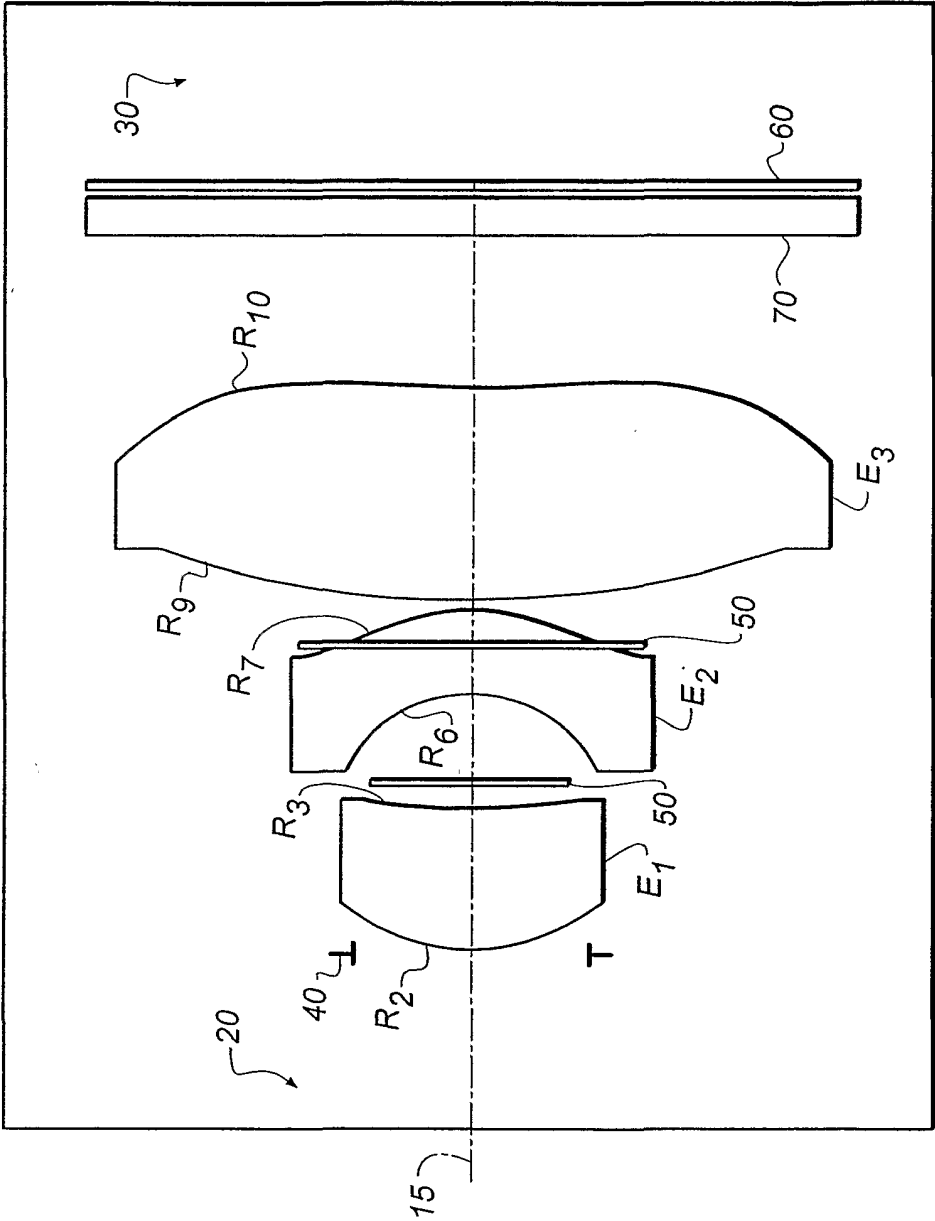


FIG. 9

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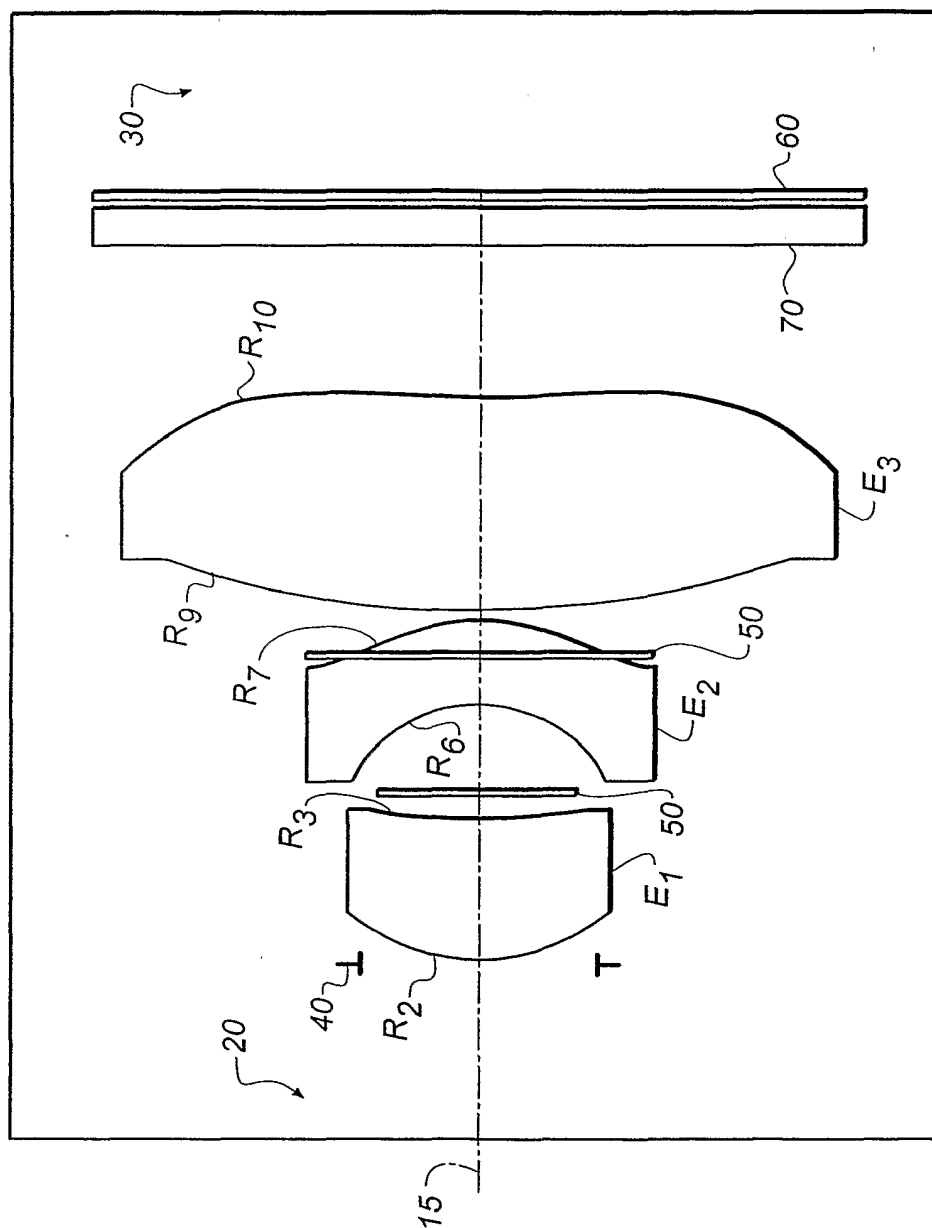
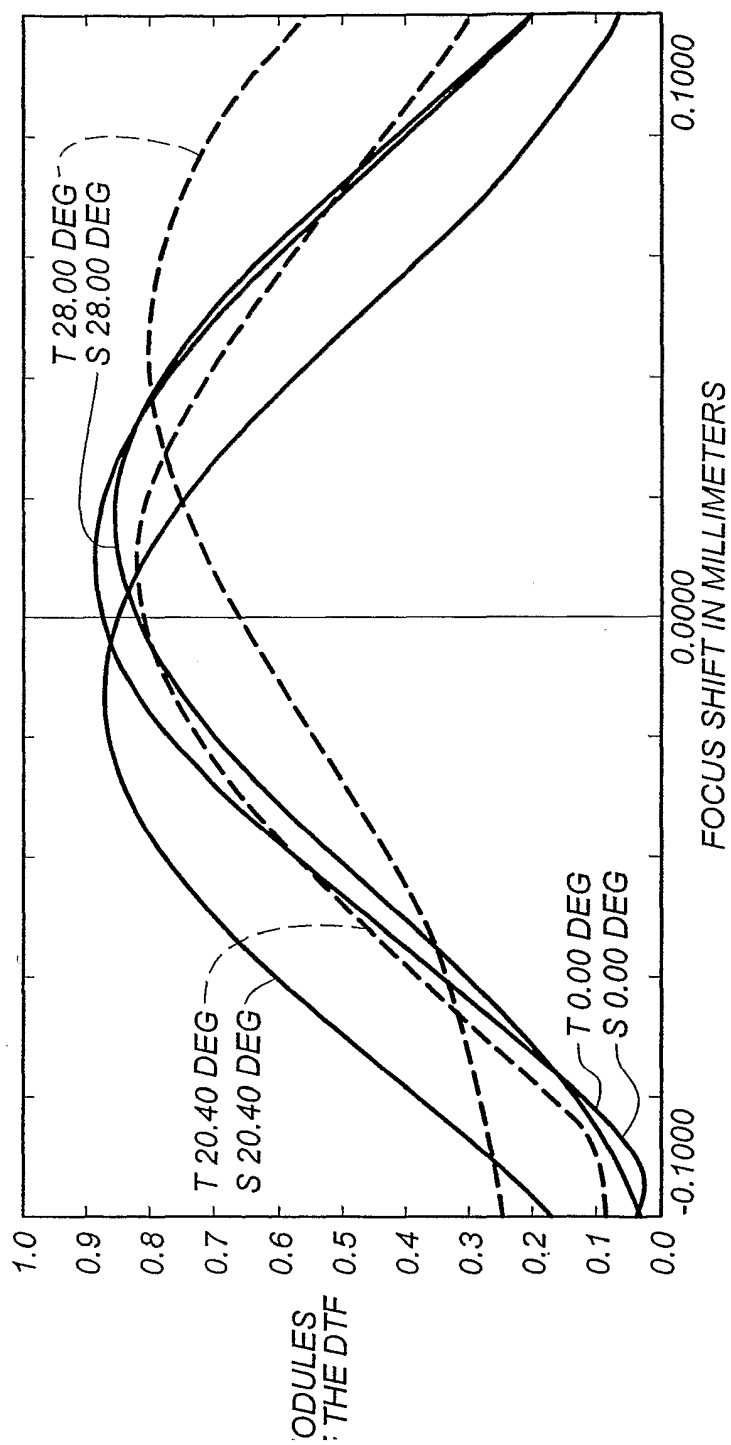


FIG. 10

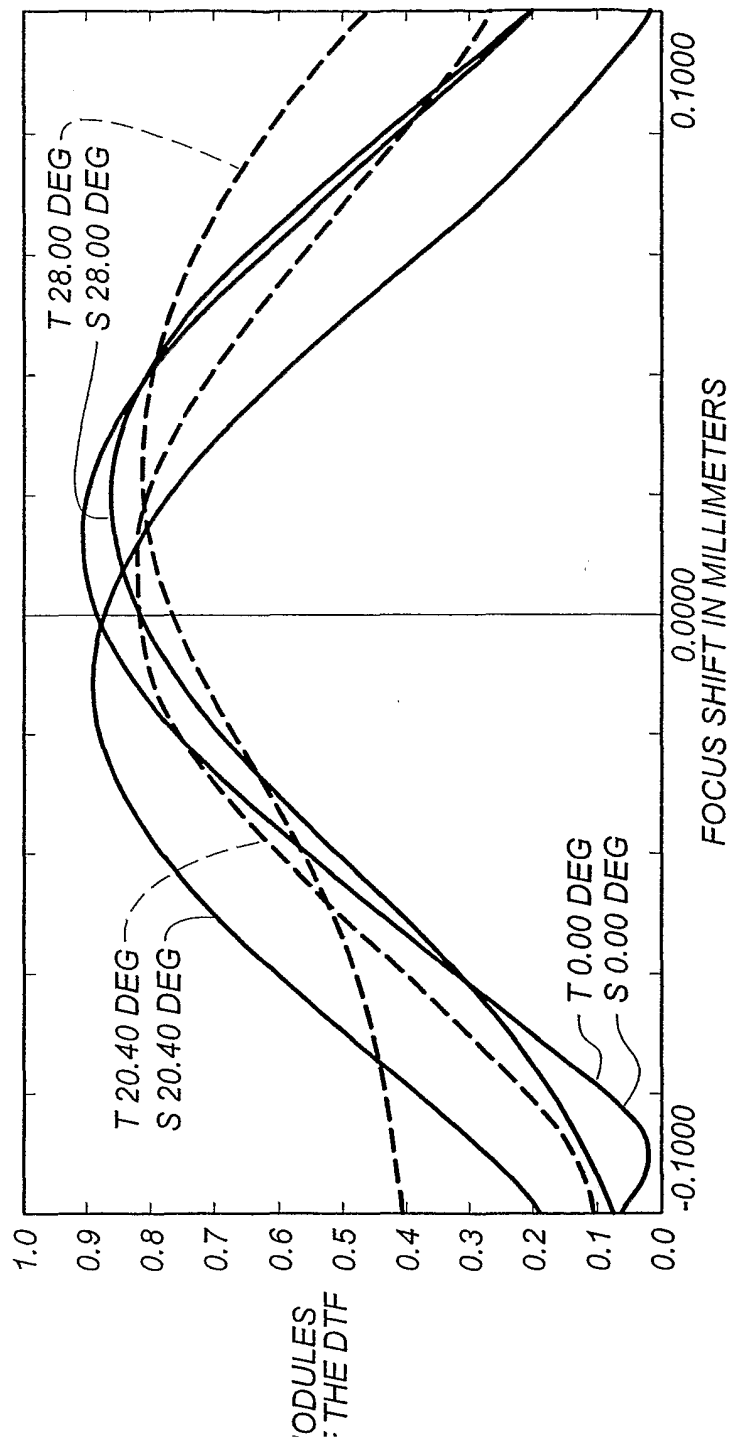
11/20



POLYCHROMATIC DIFFRACTION THROUGH FOCUS MTF

FIG. 11

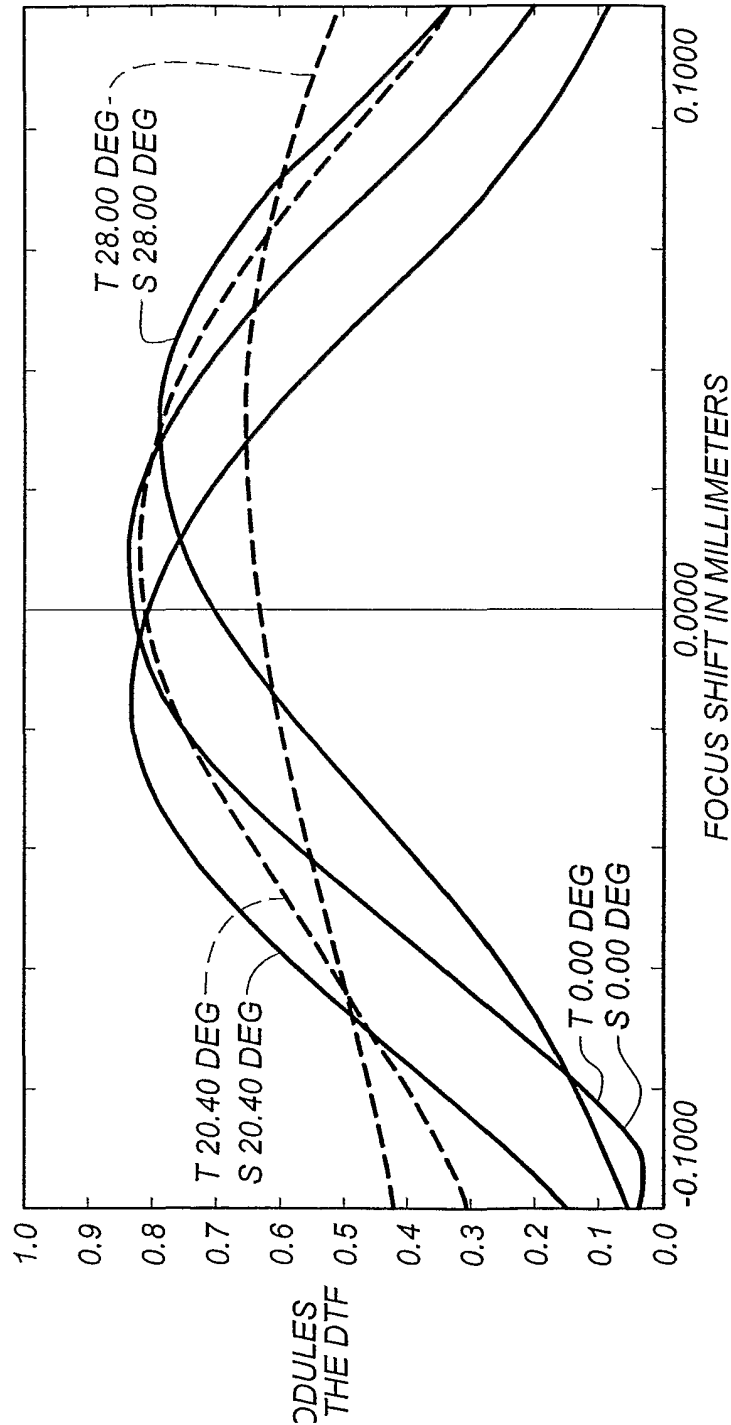
12/20



POLYCHROMATIC DIFFRACTION THROUGH FOCUS MTF

FIG. 12

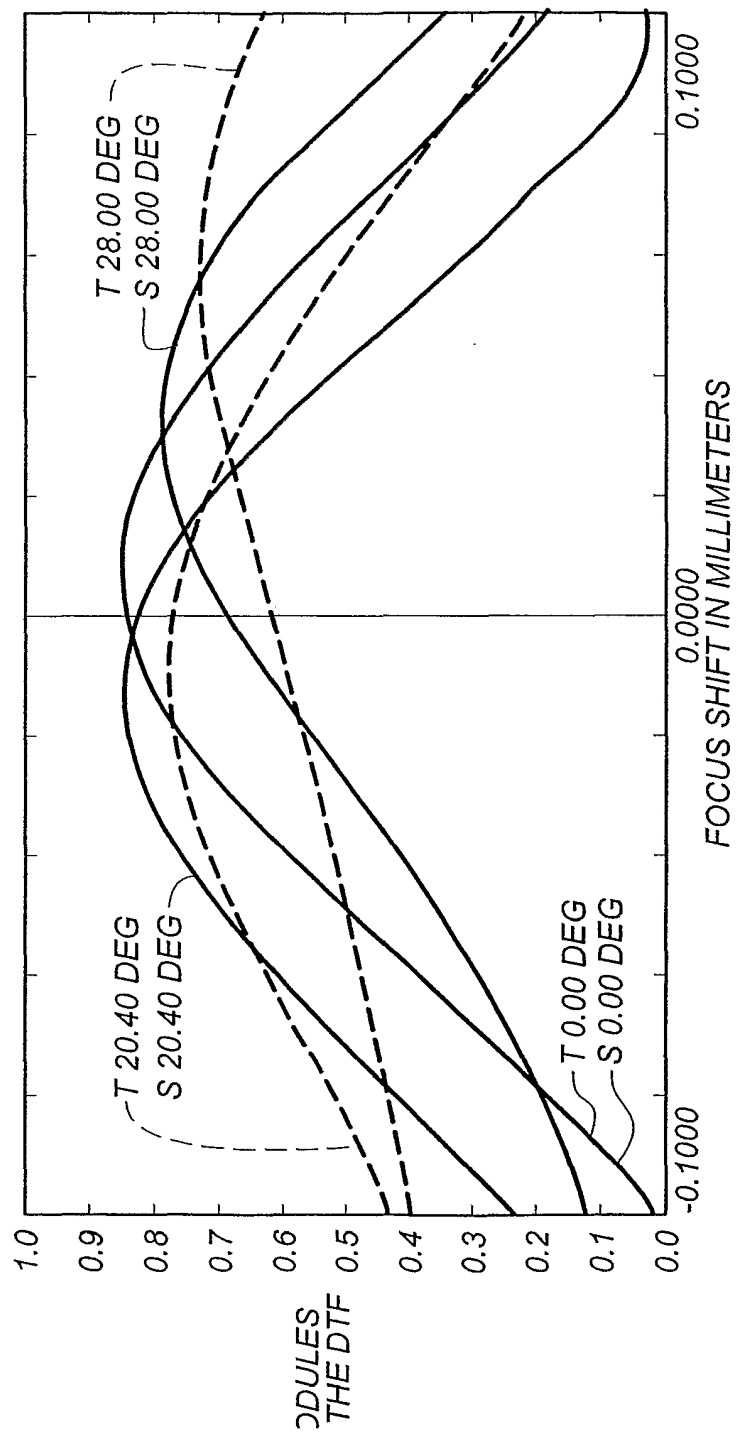
13/20



POLYCHROMATIC DIFFRACTION THROUGH FOCUS MTF

FIG. 13

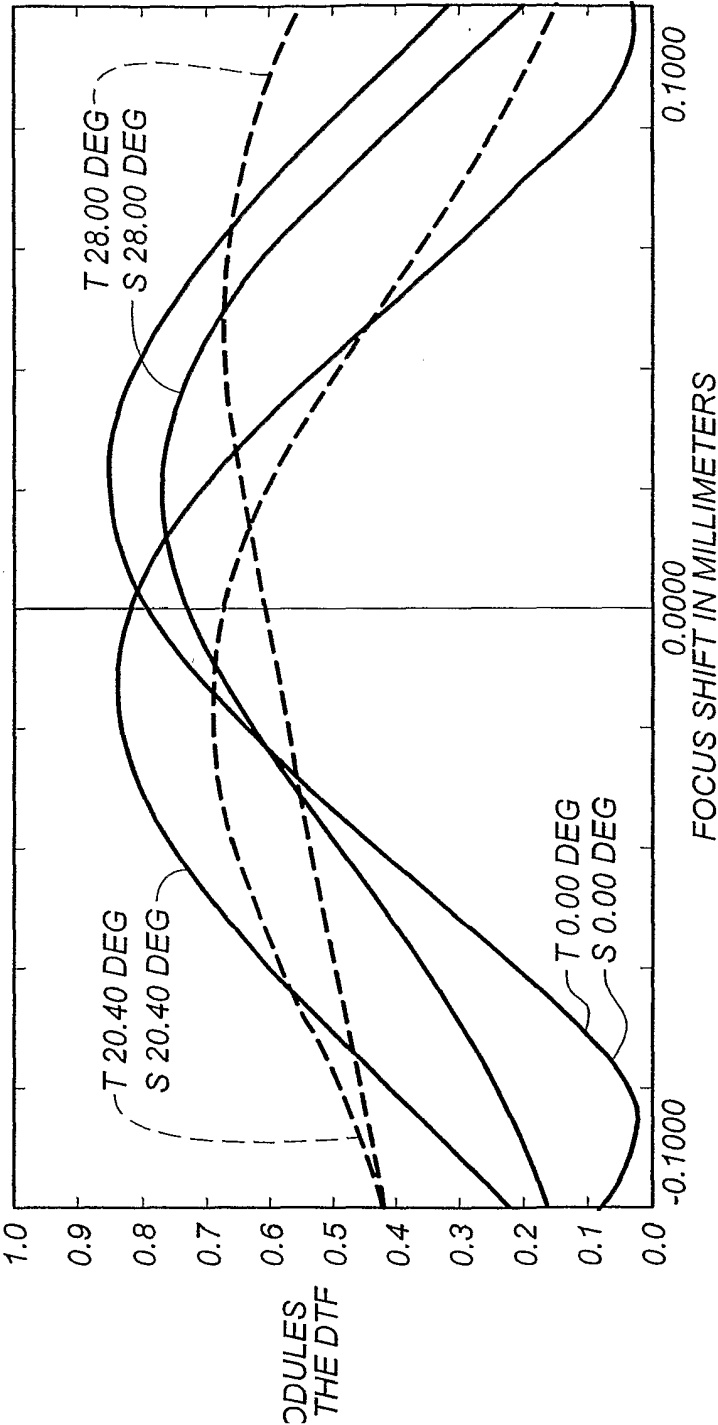
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POLYCHROMATIC DIFFRACTION THROUGH FOCUS MTF

FIG. 14

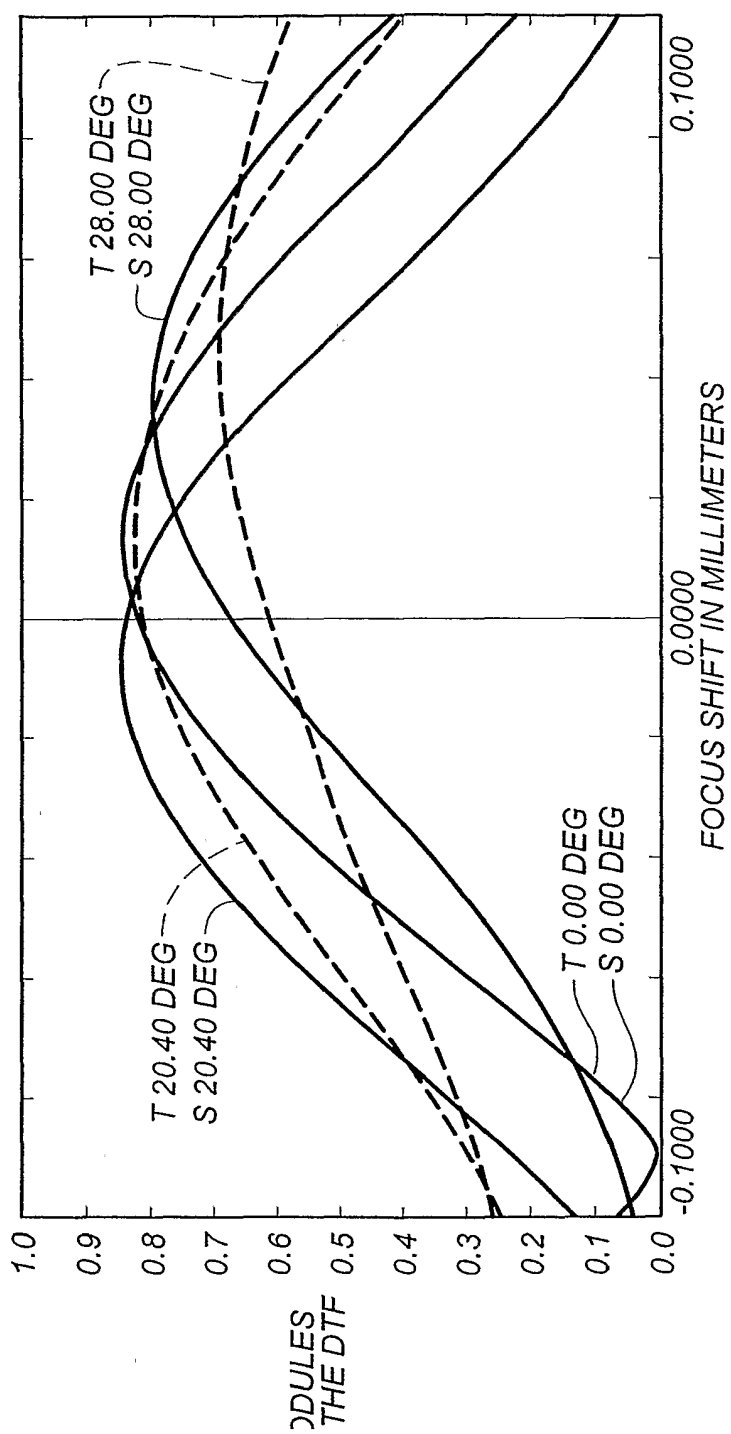
15/20



POLYCHROMATIC DIFFRACTION THROUGH FOCUS MTF

FIG. 15

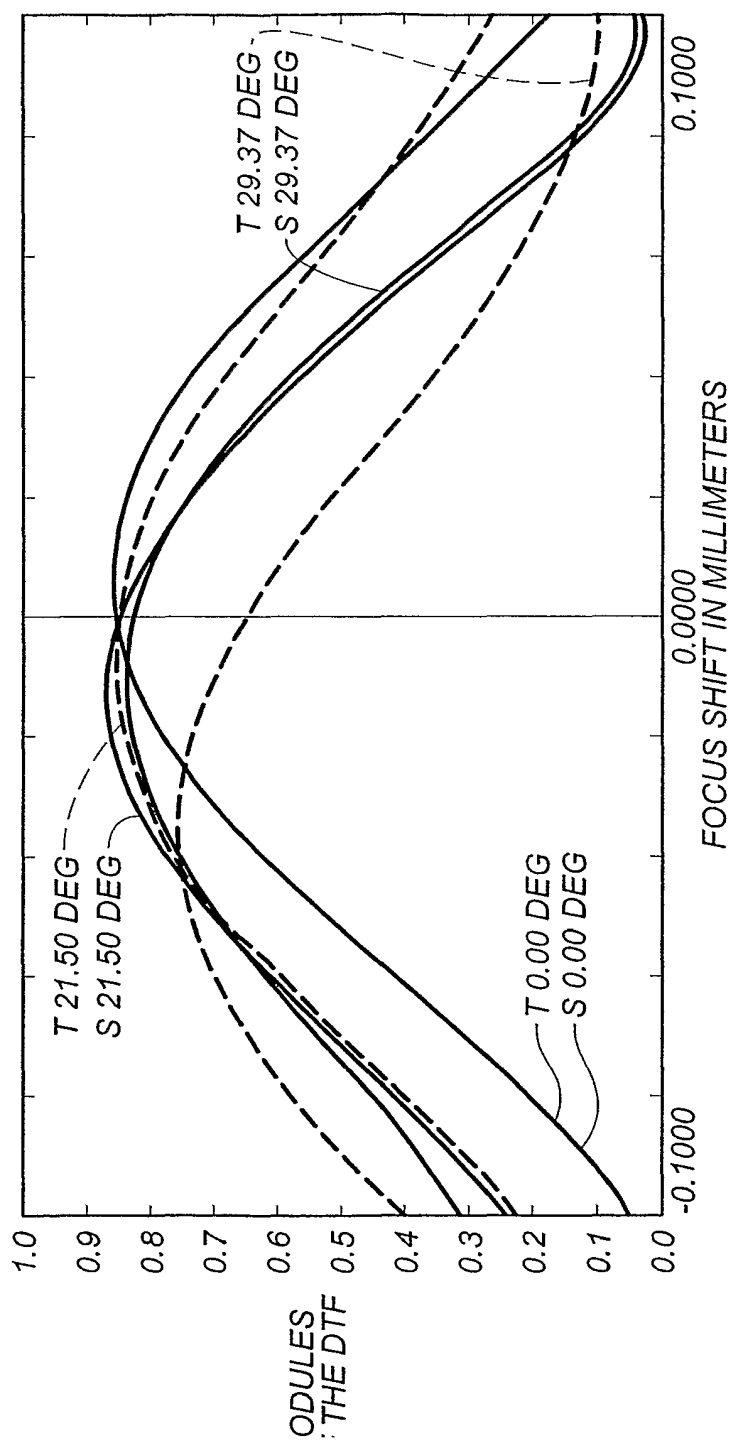
16/20



POLYCHROMATIC DIFFRACTION THROUGH FOCUS MTF

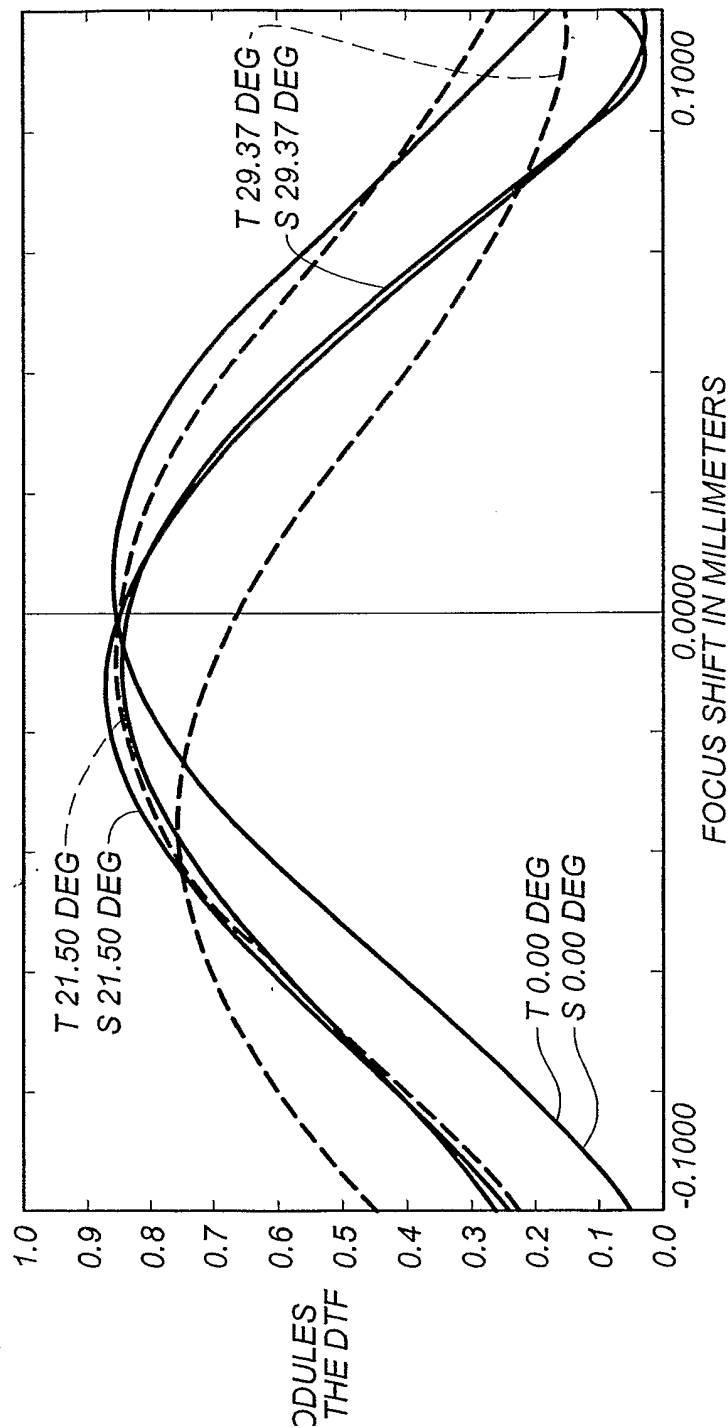
FIG. 16

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POLYCHROMATIC DIFFRACTION THROUGH FOCUS MTF

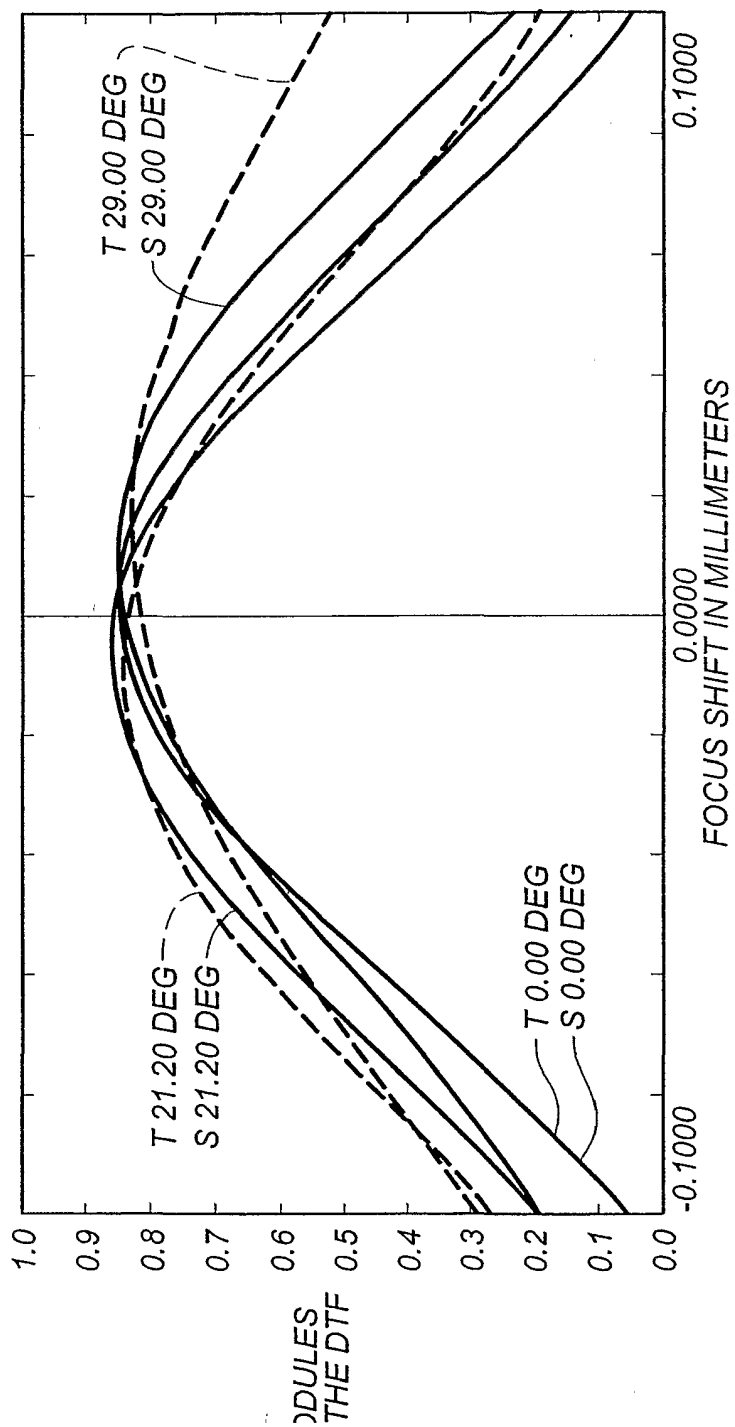
FIG. 17



POLYCHROMATIC DIFFRACTION THROUGH FOCUS MTF

FIG. 18

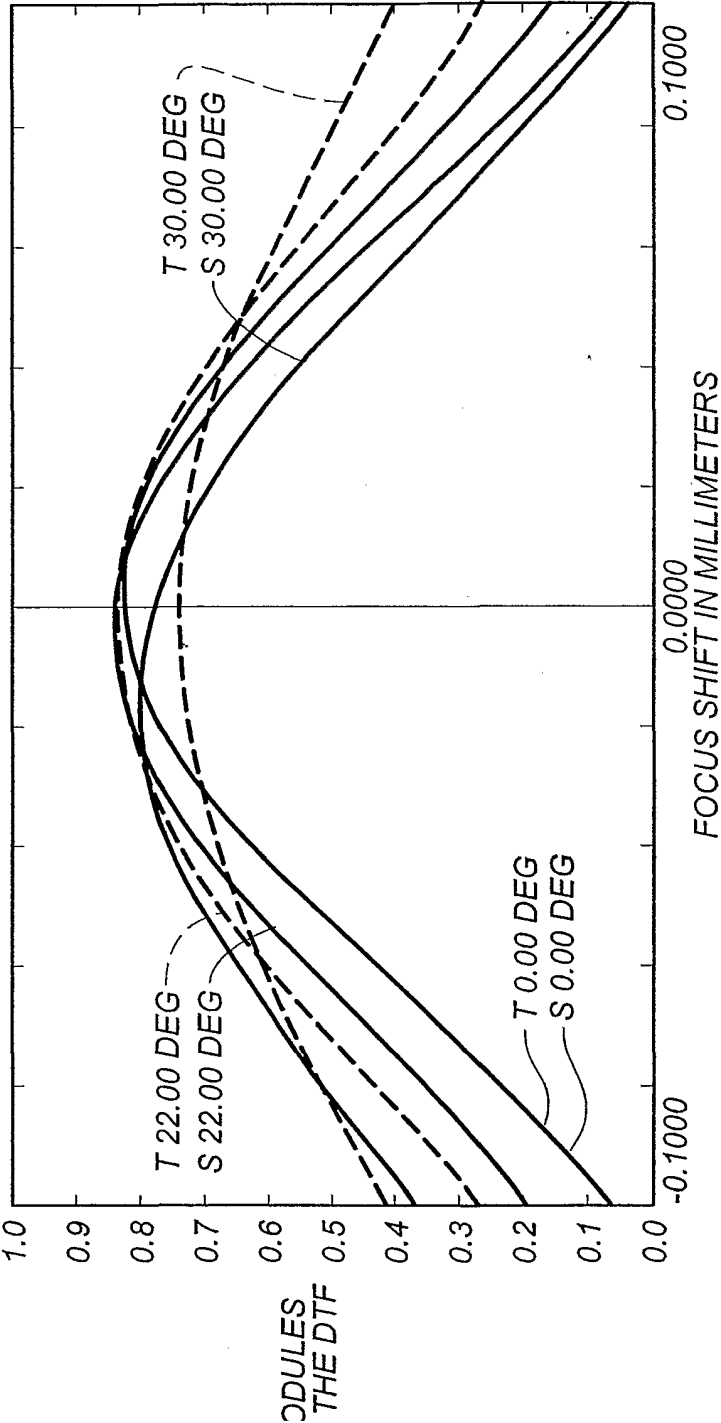
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POLYCHROMATIC DIFFRACTION THROUGH FOCUS MTF

FIG. 19

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POLYCHROMATIC DIFFRACTION THROUGH FOCUS MTF

FIG. 20

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US2004/036908

A. CLASSIFICATION OF SUBJECT MATTER

IPC 7 G02B9/14 G02B13/18 G02B13/16

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 7 G02B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, PAJ

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 3 910 685 A (DEJAGER ET AL) 7 October 1975 (1975-10-07)	1-4,6-9, 11,12, 23,28
Y	column 3, line 46 - column 4, line 6 example II; table II figure 1	5,10, 13-22, 24-27
X	US 5 940 219 A (YAMADA ET AL) 17 August 1999 (1999-08-17)	1-4,6-9, 11,12, 23,24,28
Y	example 1 tables 1-3 figure 1	5,10, 13-22, 25-27
	----- -/--	

☒ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

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Date of the actual completion of the international search

10 March 2005

Date of mailing of the international search report

22/03/2005

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European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040, Tx. 31 651 epo nl,
Fax: (+31-70) 340-3016

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von Hentig, R

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US2004/036908

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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Y	EP 1 348 990 A (KONICA CORPORATION) 1 October 2003 (2003-10-01) figure 1 paragraphs '0080! - '0084! claims 1,10 -----	5,10, 13-22, 24-27

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International Application No

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